# NEXT-GENERATION BIOFUELS: THE SUPPLY CHAIN APPROACH TO ESTIMATING POTENTIAL LAND-USE CHANGE

A Thesis
Presented to
The Academic Faculty

by

Adaora Okwo

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in the
School of Industrial and Systems Engineering

Georgia Institute of Technology
May 2012

# NEXT-GENERATION BIOFUELS: THE SUPPLY CHAIN APPROACH TO ESTIMATING POTENTIAL LAND-USE CHANGE

Approved by:


Dr. Valerie Thomas, Committee Chair
School of Industrial and Systems Engineering
*Georgia Institute of Technology*

Dr. Valerie Thomas, Advisor
School of Industrial and Systems Engineering
*Georgia Institute of Technology*

Dr. Emilson Silva
School of Economics
*Georgia Institute of Technology*

Dr. Paul Griffin
Department of Industrial and Manufacturing Engineering
*Penn State University*

Dr. Joel Sokol
School of Industrial and Systems Engineering
*Georgia Institute of Technology*

Dr. David Goldsman
School of Industrial and Systems Engineering
*Georgia Institute of Technology*



Date Approved: 1 March 2012

*To my family,*

# ACKNOWLEDGEMENTS

If it was possible to acknowledge and thank everyone who had a hand in helping me reach this important juncture in my life, this would be the longest "chapter" by far. So many have played an integral role in my academic, emotional and spiritual growth over the past few years; to each I am forever grateful. I'd like to thank my thesis committee, for their encouragement, support and insight. A special thanks goes to my advisor, Dr. Valerie Thomas, who always believed in me, supported me, gave me the freedom to explore my own interests, pushed me and challenged me to overcome my fears and who served as an inspiring example of what being a woman in academia can be. I'd also like to thank the Thomas research group, an awesome space where ideas were shared, critiqued, improved and supported—a special thanks to Seth Borin and Dexin Luo for their friendship.

I would like to thank IBM for the IBM FOCUS Fellowship, as well as the Kiplinger Fellowship for their financial support.

To my awesome family—George, Rita, Phillip and Michael—whom I love beyond words. I could not have done this without them; and it is with great pleasure that I dedicate this endeavor to them. To the entire extended Ogakwu/Okwo clan, whom I love and thank for always cheering me on. To Uncle Tony Ikebudu who prayed for me, called me regularly to check up on me and supported me in so many ways; I cannot thank him enough. And to the Anadu's and Okpukpara's who became my family here in Atlanta. When I was homesick or lonely, they always welcomed me into their home, into their family; I am eternally grateful.

Somehow I've managed to amass the most amazing group of friends in the world. They inspire me in so many ways, they provide comfort, laughter, advice, honesty

and love. There is no way I can name them all, but I'd be remiss if I didn't expressly thank Ijeoma Nwabuzor, Antoinette Murphy, Kira Valentine, Nonye Agu, Samlara Baah, Clarence Wardell III, Dimitri Hughes, Luqman Abdur-Rahman, Jolea Bryant, Sekou Remy, Melana Singletary, Helder Inacio, and Adora Nnoruka. Words cannot express how important they all are to me; I am a better person because of them.

I've been on an incredible spiritual journey since I arrived in Atlanta. I have been blessed by my church communities at Our Lady of Lourdes Catholic Church, the Georgia Tech Catholic Center, and the Cathedral of Christ the King. A special word of thanks goes out to Guillaume Porquet and the Lourdes Lunch crew, Father Mario Di Lella and Father Tim Hepburn from GTCC, as well as Father Michael Silloway at CTK.

I must recognize the support of BGSA, ASA, OMED and AASU, and give thanks for all of the relationships that were developed and cultivated through service and fellowship within each organization. A heartfelt thanks goes out to Jackie Cox and Dr. Felicia Benton-Johnson. And I am especially appreciative of the library and Clough Commons staff that has seen me through *many* late night study sessions.

My time in Atlanta would not have been the same without Umu Igbo Unite, Panthers softball, and countless others whom I'm sure I have forgotten to mention. When I started this program I had no idea just how rich my experiences would be, the things I would learn about myself, or the people I would come to love so dearly. Now that this chapter is complete, I look forward to the experiences, lessons and new found loves of the chapters to come. I praise God for His mercy and His grace.

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# SUMMARY

Biofuels, including ethanol and biodiesel, are important components of energy policy in the U.S. and abroad. There is a long history of ethanol production from corn (maize) in the United States and from sugarcane in Brazil. However, there has been a push for greater use of next-generation biofuels (including those derived from cellulosic feedstocks) to mitigate many of the environmental and potential food system impacts of large scale biofuel production.

Farmer willingness to grow biomass crops and ensuring adequate feedstock supply are two important challenges impeding large scale commercialization of next-generation biofuels. The costs of transporting bulky, low density biomass will be substantial. Consequently, in the near term, the economic success of next-generation biofuels will hinge on the supply of locally available biomass. As such, agricultural contracts are expected to be an important tool in overcoming the feedstock acquisition challenge. The broad objective of this study is to understand the effect of contracting for non-food energy crops (cellulosic feedstocks) on the agricultural landscape via the displacement of commodity (food) crops on productive cropland.

We develop an analytical framework for evaluating the design and use of two different contract structures for securing cellulosic feedstock in a representative supply chain with a biorefinery and farmer. We study the dynamics of scarce land and indirect competition from commodity market production on a biorefinery's equilibrium pricing strategy and the resultant supply of cellulosic biomass. And we consider its sensitivity to various production characteristics and market conditions.

We develop a method for quantifying the biorefinery's tradeoff between profit margins and competing for land in order to secure the requisite feedstock for biofuel

production. And we characterize the loss of efficiency in the decentralized system, relative to a vertically integrated system, that can be attributed to the need to compete for the farmer's scarce land resource versus that which results from the biorefinery's desire to make a profit.

Then we extend our framework to consider multi-year contracts for biomass production and evaluate the importance of land quality, yield variability and contract structure on a farmer's willingness to accept a contract to produce cellulosic feedstock as well as the resulting impact on the agricultural landscape through the displacement of commodity crops. Using switchgrass production in Tennessee as a case study, we develop feedstock supply curves for each contract structure considered and evaluate the conditions and contract prices at which land devoted to various field crops would be displaced by switchgrass based on field trials of switchgrass production in Tennessee and recent USDA data on crop prices and production.

# CHAPTER I

# INTRODUCTION

## 1.1 Background & Motivation

Biofuels (ethanol and biodiesel) are an important component of U.S. energy policy. Recognizing the need to reduce dependence on foreign oil and mitigate climate change, regulatory support for biofuels was enacted in 2005 with passage of the Energy Policy Act—which established the Renewable Fuel Standard (RFS)—and was significantly expanded in 2007 with the Energy Independence and Security Act (EISA). There is a long history of ethanol production from corn (maize) in the United States. The decade up to 2009 saw considerable growth in production, increasing from 1.46 billion gallons in 1999 to 10.76 billion gallons in 2009 [34].

There has been much debate, however, regarding the efficacy of first-generation biofuels (such as ethanol from corn) in meeting energy and environmental goals. For discussion on fossil energy consumption in the ethanol production process see [101, 90, 122, 70]; environmental impacts, see [99, 44, 45]; and, impact on food prices [81, 53, 118, 98, 5]. Next-generation biofuels have the potential to mitigate many of these concerns [105]. Indeed, the RFS, which mandates 36 billion gallons of renewable fuel use by 2022, caps the amount that can be met by traditional (corn) ethanol at 15 billion gallons and calls on advanced biofuels, including next-generation biofuels, to constitute the difference.

To date, production of next-generation biofuels, particularly cellulosic ethanol, has fallen woefully short of expectations.[1] There are several key challenges preventing large scale commercialization of cellulosic biofuels. These include: high production costs and capital outlays; accessing financing alternatives in the pre-commercial development phase; farmer willingness to grow new energy crops; ensuring adequate feedstock supply; and, the blend wall constraint which limits the share of ethanol blended in gasoline to 10% [26, 100]. In this thesis, we focus our attention on the challenges of gaining farmer participation and ensuring an adequate supply of biomass feedstock.

A number of biomass feedstocks can be used to produce cellulosic biofuel, including: agricultural crops, crop residues, wood and wood waste, algae, and municipal solid waste. However, of the companies on public record as having plans to produce next-generation ethanol, approximately 50% will rely exclusively on agricultural feedstocks, including dedicated energy crops like switchgrass [26]. These feedstocks are bulky with low density; consequently, transportation costs are substantial [95]. And, unlike ethanol produced from corn, a well-developed infrastructure system for their production, harvest, storage, and purchase does not yet exist [35]. As such, securing a reliable supply of feedstock will hinge on the availability of biomass in close proximity to biofuel facilities [82].

There has been substantial work done in the area of estimating potential feedstock supplies. Much of this work has derived supply curves based on estimates of the cost of production [89]. While production costs are an important factor affecting potential supply, recent surveys of farmer willingness to supply switchgrass have identified various risk factors as impediments to large–scale production. These impediments include "the increased complexity associated with alternative farming; the need for

[1] In 2010, the Environmental Protection Agency (EPA) announced that it would reduce that year's mandated production from 100 million gallons to a mere 6.5 million.

additional training, information and capital outlays; ... and concerns about the absence of secure, reliable markets" among others [60]. The importance of anticipated returns to alternative uses as a key factor in agricultural land use decisions has been cited in [73].

The importance of locally available feedstock and the factors affecting an agricultural producer's willingness to produce the necessary feedstock suggest that contracting can play a significant role in mitigating these particular challenges to cellulosic biofuel expansion. It is from this perspective that we propose a supply chain management approach to estimating potential feedstock supply and assessing the impact of contracting for bioenergy crops on the agricultural landscape via the displacement of commodity crops.

This thesis is composed of three main chapters. Chapter 2 builds the supply chain framework employed in our analysis of feedstock supply. We assume a two-echelon decentralized supply chain in which a biorefinery offers a representative agricultural producer (farmer) a contract to produce an energy crop required for biofuel production. We consider the optimal terms of trade under two different contract structures, evaluate the conditions under which the farmer is willing to accept the terms of trade, and, upon acceptance, how the farmer decides to allocate her fixed capacity (land) resource between energy crop production and production of an alternative (commodity) good. Using an integrated supply chain as a benchmark, we evaluate the tradeoffs faced by the biorefinery in determining terms of trade, and its impact on supply. We also consider the impact of various market and production conditions on equilibrium outcomes.

Chapter 3 explores the impact of commodity (spot) market production on participation (contract acceptance) and capacity allocation in the supply chain framework from Chapter 2. Our primary analysis assumes a farmer who accepts a contract for energy crop production will add the energy crop to her existing crop mix at a scale proportional to its profitability. However, agricultural surveys show that farmers who produce under contract do so for a variety of reasons and at a variety of scales. We compare the contract design problem from the previous chapter with contract design for a farmer who will "specialize" in production of the contracted good and evaluate the explicit versus implicit effects of commodity market competition on the supply chain for biomass feedstock. We also evaluate the merits of breakeven pricing under both modeling approaches.

Finally, in Chapter 4 we extend the framework developed in Chapter 2 to develop supply curves based on multi-year versions of the two contract structures in order to assess the impact of contracting for biomass on the agricultural landscape. Using contracts for switchgrass production in Tennessee as a case study, we also incorporate many unresolved issues in biomass production and assess their impact on the economic feasibility of switchgrass production and the agricultural landscape. This model is particularly useful in evaluating the importance of yield variability (both temporal and geographic) and assumptions on the commercial scalability of switchgrass production as it pertains to the prices at which switchgrass production is competitive with traditional commodity crops. And, by considering potential supply at the county level, our model provides more refined estimates which can aid in the determination of where to site biorefineries.

# CHAPTER II

# AGRICULTURAL CONTRACTING FOR FEEDSTOCK SUPPLY

## *2.1 Introduction*

The tools of operations research (OR) have been used extensively to study agricultural production planning, particularly as it relates to land allocation and optimal crop mixes. Recent work by Kazaz [61] and Kazaz and Webster [62] has considered planning in the face of yield dependent costs and prices. Ahumada and Villalobos [4] review the production and distribution planning literature related to agri–food supply chains. In addition to reviewing the literature in which OR has been used to study crop production, Lowe and Preckel [72] identify new areas for which OR can aid agribusiness. Contracting is one area for which research has been deemed necessary.

There is ample literature on contract theory [15, 55, 66, 97]. In the agricultural context, contracting studies have focused primarily on moral hazard, particularly as it relates to sharecropping and leasing land from a landlord [3, 39].[1] However, despite its growing use in practice, the literature on contracts for agricultural production is rather limited. Wilson and Dahl [124] provide a broad survey of the terms and clauses in grain contracts; Sykuta and Parcell [104] provide a survey of the terms in contracts for identity-preserved nongenetically modified soybeans. Preckel et al. [91] consider the link between contract structure and environmental externalities by comparing the use of nitrogen fertilizer—and consequently nitrate leaching into groundwater—in response to a secure, fixed-payment structure versus the insecure tournament contract

[1] There is a long history of agricultural contracting for land, credit and equipment; the use of contracts for agricultural production (particularly as it relates to crops other than vegetables used for processing) is a rather recent phenomenon [75].

structure which is common for livestock and seed corn production. And Carriquiry and Babcock [23] consider the economic factors which lead farmers and processors to supply (procure) a particular commodity via contract versus the spot market.

Paulson and Babcock [87] and Larson et al. [68] have studied the role of contract structure in agricultural supply. Paulson and Babcock model the equilibrium supply of specialty grains under two production contracts—acreage and bushel. Their acreage contract is analogous to the wholesale contract we consider here. They assume a participating farmer will allocate all of her land toward production of the contracted specialty good, while a non-participating farmer uses her entire land resource to produce commodities for the spot market. The farmer will participate provided the processor's contract premium is sufficient to cover the additional cost of specialty crop production which is private information held by each farmer.

The Larson et al. study is a bioenergy application in which the expected supply of feedstocks for ethanol production by a representative agricultural producer is evaluated under four contracting alternatives and varying degrees of risk–aversion. The model we present in this chapter is similar to [68] in that we also consider an agricultural producer's land allocation decision between energy crops (biofuel feedstocks) and traditional commodity (food) crops in response to different contract structures. However, we extend their work to include the optimal decisions of a representative biorefinery who must determine terms of trade (contract parameters) in order to secure the desired supply of feedstock. And, since our goal is to understand how contract structure reduces barriers to the *establishment* of a market for bioenergy feedstock, we make a key assumption that no spot market exists for the exchange of energy crops. In the absence of a spot market, a biorefinery's supply of feedstock is limited to what it can induce via contract terms.

Like Paulson and Babcock we are interested in evaluating the conditions under which an agricultural producer will choose to participate in contracted production of a specialty crop. And like Larson et al. we are interested in evaluating the producer's scale of participation, via the land allocated to a specialty crop under various market and production conditions. However, in addition to modeling an agricultural producer's decision to participate in the supply chain for next-generation biofuels by growing the requisite feedstock, this chapter models the contract design problem in light of the producer participation problem. Our primary objective is to analyze the optimal specification of contract terms in order to secure a desired supply of feedstock.

We consider two contract structures: the wholesale (price-only) contract and what we call a capacity procurement contract. Using a supply chain management framework, we model an agricultural producer's decision to allocate her fixed land resource toward production of a risky good (bioenergy feedstock) under contract, and traditional food/commodity goods for sale on the spot market.[2] Taking the producer's land allocation response into account, the biorefinery must determine the terms of trade balancing his own profit goals with the need to compete for the producer's resource.

Under wholesale contract, the biorefinery pays for each unit of feedstock (biomass). This forward cash contract structure, which dictates the terms of exchange, is representative of the *marketing contracts* typically used in contracts for major field crops. Under capacity procurement contract, however, the biorefinery pays the producer for each unit of land she allocates toward production of the feedstock. This contract structure is similar to *production contracts* which are commonly used in livestock procurement. Production contracts typically pay an agricultural producer for services rendered in the production of a commodity; the contractor retains ownership of the commodity while it is under production [76]. We evaluate the role of contract structure on the producer's allocation decision, the relationship between contract pricing

[2] While there is uncertainty associated with all agricultural production due to weather conditions, pests, etc., we focus on the uncertainty due to complexity and unfamiliarity with alternative farming, as expressed by the farmers surveyed in [60].

and market conditions, and overall system performance.[3]

In the next section we frame our work within the supply chain management literature. In §2.3 we describe the basic model framework and provide a list of notation. §2.4 presents the optimal solution for an integrated supply chain which we use as a benchmark in analyzing the wholesale and capacity procurement contracts. §2.5 compares the performance of each contract structure using a numerical case study. And §2.6 concludes. Proofs not included in the text can be found in the appendix.

## *2.2 Literature Review*

There is a rich collection of work on contracting, performance and coordination in the supply chain literature [108, 67, 19]. To position our work we limit this review to capacity procurement and capacity allocation literature.

In the procurement literature a buyer (manufacturer or retailer) enters into a contractual arrangement with one or more suppliers who will produce components which the manufacturer will sell to its customers (perhaps after processing or assembling with other components). Typically, the supplier(s) must build capacity at a constant, per unit cost well before the buyer learns the actual size of his market (i.e. demand for the manufacturer's final product is uncertain at the time the supplier must build capacity). Once his demand is realized, the manufacturer purchases the requisite components in an amount equal to the minimum of demand and the supplier's installed capacity.

The risks imposed by high investment costs, long lead times for building capacity and uncertainty in demand for the manufacturer's product tend to discourage suppliers from significant expansions in capacity [37]. When demand is high, limited capacity can lead to significant lost sales for both the supplier and manufacturer,

[3] Throughout we adopt the convention that "he" refers to the biorefinery while "she" refers to the agricultural producer/farmer.

resulting in poor system (supply chain) performance. But when capacity is substantial and demand is low, performance is degraded through the losses associated with underutilization. Contracting allows the supplier and manufacturer to share these risks so that supply chain performance can be improved.

Sharing demand forecasts is one method manufacturers use to encourage adequate capacity. However, since the manufacturer typically only pays for the capacity needed to satisfy his demand, he has an incentive to inflate his demand forecast in order to motivate greater capacity investment that would allow him to take advantage of potential high demand scenarios. Understanding this incentive for the manufacturer to overestimate his demand, the supplier will use her own, potentially less informed, assumptions about demand to make the capacity investment decision best for her; this can lead to substantial inefficiencies within the system. A number of risk sharing contracts have been put forth in the literature to reconcile this source of inefficiency.

Quantity flexibility contracts share risk and reduce inefficiency through bounds on the manufacturer's forecast. The manufacturer submits his forecast to the supplier and agrees to purchase at least a certain percentage of that forecast while the supplier agrees to have available capacity at least a certain percentage above the forecast [109]. Quantity commitments, such as minimum purchasing agreements, provide credible forecasts for the supplier. As such, they allow the manufacturer and supplier to share the risks arising from uncertain demand better; they ensure a market for the supplier's product; and, they ensure a minimum component supply for the manufacturer [8]. See [7, 10, 11] for more on quantity commitments.

Options contracts are similar to minimum purchasing agreements but they offer the manufacturer a greater degree of flexibility in responding to market conditions through the exercise of options for additional components after demand has been realized [8]. Barnes–Schuster et al. [9] study the flexibility of options in a two-period context where options can be exercised after realization of first period demand but before the realization of second period demand. Cachon [19] studies an options contract with a single demand period; but, unlike [9], the manufacturer does not make any firm purchase commitments in addition to the options he purchases. Erhun et al. [36] consider a two-period model in which the manufacturer has two procurement opportunities and a timing option; an option to purchase after demand has been realized at an exercise price equal to the supplier's second period wholesale price.

Unlike the aforementioned contracts we do not consider demand uncertainty or explicit demand targets. In the particular context which motivates this study, U.S. energy policy guarantees a market for biofuel via the Renewable Fuel Standard. Rather, our focus is on the economic feasibility of procuring a target level of biomass, with a particular emphasis on the impact of competition for scarce land resources. Due to long *production* lead times—as opposed to the long capacity building lead times typically considered in the supply chain literature—the flexibility offered by the aforementioned contract structures is not appropriate in our context. And, in addition to considering a wholesale (price-only) pay structure, we consider a structure in which the supplier is paid for the capacity allocated toward production, as opposed to the amount of output produced.

Capacity (land) allocation is inherent to our biomass procurement problem. In the supply chain literature, determining capacity is analogous to choosing a maximum production level. The capacity allocation problem is typically studied in the context of allocating a fixed supply of homogeneous goods between retailers (buyers). Cachon and Lariviere [21] model a decentralized supply chain in which a single capacitated supplier sells to multiple independent retailers. Retailers submit orders to the supplier in advance of their selling season; if retailer orders exceed the supplier's fixed capacity level, a pre-specified allocation mechanism is used to determine each retailer's delivered quantity. Cachon and Lariviere [20] study the capacity allocation problem using past sales to determine a retailer's allocation.

As in our model, the suppliers fixed capacity indirectly results in competition between otherwise independent sources purchasing the suppliers products. However, in our model the supplier determines her optimal allocation between distinct products—as opposed to allocation of a single product between distinct buyers—and she has no influence over total capacity in any stage. Because we assume the supplier produces one product for a spot market and one under contract, the "competition" for capacity is one-sided and indirect. With full information, the buyer offering a contract under this type of competition can use his knowledge of spot market conditions, as well as conditions in his own market, to influence the supplier's choice of allocation. We are interested in a profit maximizing buyer's (biorefinery) design and use of contract terms as a means of securing a share of the supplier's (farmer) scarce capacity (land) resource.

To our knowledge, Mazzola and Schantz [78] is the only paper that considers a capacitated supplier who must decide how to allocate her fixed resource between distinct production processes. They, however, consider the allocation problem from the perspective of (dis)economies of scope. We assume no jointness in the production process for the contracted and commodity good so that (dis)economies of scope is not an issue.[4] Jointness does arise, however, through allocation of the fixed capacity resource. For more on jointness in agricultural production due to fixed but allocatable inputs see [102, 74, 84].

Random yields have been studied extensively in the context of production–inventory systems; see [126] for a review. We are not aware of any papers that address random yield or random supply in a capacitated supply chain context. Supply (yield) uncertainty is important in an agricultural producer's decision process. We make two

[4]In other words, we assume there are no interdependencies in the production process such as equipment sharing, scheduling complementarities/conflicts, or co-production.

assumptions which reduce supply uncertainty to its simplest form: agricultural producer's who contract are risk neutral, and the random shock which effects the supply of biomass available at harvest is independent of the producer's land allocation.[5] As such, supply uncertainty can be characterized by its mean (expected value).

Contracting in an agricultural context has been taken up by Boyabatli et al. [16] and Burer et al. [18]. Boyabatli et al. model optimal procurement in the beef supply chain when a packer can contract for cattle and make purchases on the spot market. They consider window contracts, in which the contract price is a linear function of the spot price. Burer et al. consider coordination in the agricultural seed industry. A single supplier determines contract terms with the goal of coordinating the ordering decisions of independent dealers who in turn, sell seed to farmers. They consider a pure bonus system in which dealers receive a bonus when sales meet or exceed a target fraction of his order quantity, and a mixed system which adds a penalty to the bonus system for falling short of selling a specified fraction of the order quantity. The wholesale price at which seeds are sold to dealers is exogenous to the model; the supplier determines the target fractions, bonus and penalty payments.

Agricultural contracting has been studied most prominently in the livestock sector. However, the literature on contracting for field crops is limited. Major field crops, oilseeds and grains, are predominantly sold as commodities. However, the recent increase in demand for special attributes that are costly to identify in spot markets, and several other factors, has led to an increase in the value of contracted field crop production [75]. The literature addressing this area has been slow to follow.

---

[5] 92 percent of the agricultural production under contract in 2008 was on commercial farms [76]. The uncertainty we consider here is that due to unfamiliarity in producing a new crop, thus, it is unlikely to vary with the scale at which the new crop is adopted.

## *2.3 Model Framework*

Consider a two-echelon supply chain with a single multi-product supplier (e.g., agricultural producer) and a single manufacturer (e.g., biorefinery). There is a non-substitutable (critical) component required by the manufacturer's production process which can only be produced by the supplier (e.g., biomass feedstock). The supplier has fixed production capacity (e.g., land) which she must decide how to allocate between various commodity products and the critical component at the beginning of the period. The supplier's production process is characterized by a long lead time, sunk costs and yield uncertainty in production of the critical component. Consequently, once capacity has been allocated adjustments cannot be made and the output for each product is not realized until the end of the period.[6]

The commodities produced by the supplier are sold on the spot (commodity) market. The manufacturer's industry, on the other hand, is still nascent. There are not enough buyers and sellers for a spot market to exist for the critical component. In order to guarantee supply of the critical component, the manufacturer must establish a contractual arrangement with the supplier.

The supplier's total capacity $L$ is allocated between products $i \in \{1, \ldots, n\}$. Capacity allocated to product $i$, denoted $L_i$, has per unit capacity cost $c_i$. However, before the supplier can produce any of the manufacturer's components, an additional fixed set up cost $s$ is incurred. Total output of product $i$ is an increasing, twice-continuously differentiable, concave function of the allocated capacity, given by $Q_i = f_i(L_i) \equiv (\beta_i - \delta_i L_i)L_i$.[7] Output of the critical component, however, is subject to

[6] Typically the supply chain literature assumes that capacity and production are independent decisions. In our case, however, by choosing capacity, the supplier simultaneously chooses her expected production quantity.

[7] This particular output function decreases marginal output per unit capacity as a linear function of the allocated capacity [58]. In the context of agricultural production, it can be used to reflect reductions in yield as a result of varying land quality or a supplier's preference for diversification. We assume the supplier's capacity endowment is such that marginal output is always non-negative. In other words, $f_i'(L) \geq 0 \; \forall i$.

a random, positive, multiplicative yield shock $\tilde{\epsilon}$ with cumulative distribution $G(\cdot)$, probability density function $g(\cdot)$, support $[\underline{\epsilon}, \overline{\epsilon}]$ $(0 \leq \underline{\epsilon} < \overline{\epsilon} < \infty)$ and finite mean. Thus, total output for the critical component, which we designate with index $n$, is $Q_n(L_n, \tilde{\epsilon}) \equiv f_n(L_n)y(\tilde{\epsilon})$. We assume the output function, $f_n(\cdot)$, is independent of the yield distribution $G(\cdot)$; also, $y(\underline{\epsilon}) \geq 0$ and $y'(\tilde{\epsilon}) > 0$.

Common knowledge and full information are assumed; both the supplier and manufacturer have the same beliefs regarding the yield distribution, and all cost and market parameters are known by both parties. We assume the spot price for each commodity $i$ is a random variable that is independent of the prices and yields of all commodities and has expected value $\mathbf{p} = (p_1, \ldots, p_{n-1})$.[8] For simplicity and ease of exposition we analyze the case in which the supplier produces one (aggregate) commodity good and the critical component (i.e., $n = 2$).

The manufacturer is a price-taker in the market for his end product (e.g. biofuel) but a Stackelberg leader in any contractual arrangement entered with the supplier. The manufacturer faces an exogenously determined (retail) price with expected value $\alpha$ and constant marginal processing cost $k$ for each unit of his end product. He procures the critical component from the supplier at contract price $\omega$ and transforms it into a unit of the end product at the fixed input-output ratio $\gamma$. A timeline of the game is illustrated in Figure 1.

### 2.3.1 Notation

From here on we use terminology consistent with our specific application. The farmer (supplier) must determine how to allocate her fixed land (capacity) resource toward the production of commodity (food) crops for the spot market and energy crops/biomass (components) under contract for a biorefinery (manufacturer). For convenient reference we list the notation used throughout this dissertation. Decision

[8] We assume the spot price is independent of commodity yields since we are considering a single farmer in a competitive industry.

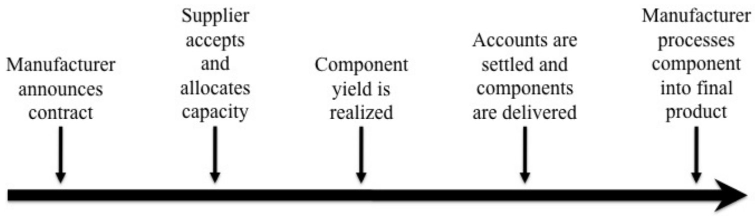



Figure 1: Sequence of Events

variables are designated (DV), random variables are designated (RV).

## *2.4 Supply Chain Structures*

### 2.4.1 Integrated Supply Chain

Volume and profit are key indicators of a viable biofuel industry. As a benchmark we consider a channel in which the biorefinery and farm are vertically integrated; the biorefinery owns and operates the cropland, for example. We assume, however, that the vertically integrated channel will only use cropland for the production of energy crops. The biorefinery can sell all of the biofuel it produces at the market price $\alpha$.[9] In the integrated system, the amount of land used to grow energy crops maximizes expected profit from biofuel production:

$$E[\Pi^I] \; = \; \max_{0 \le L_2 \le L} \quad E[\gamma(\alpha - k) f_2(L_2) y(\tilde{\epsilon}) - c_2 L_2 - s] \tag{1}$$

The unique optimal land use for energy crop production in the integrated system is:

$$L_2^I \; = \; \min\{L_I^\star, \, L\} \tag{2}$$

where $L_I^\star$ satisfies the first order condition:

$$f_2'(L_I^\star) = \frac{c_2}{\mu\gamma(\alpha - k)}$$

We focus on the case in which the fixed set up cost $s$ is not prohibitively large so

[9]For example, there is a guaranteed market for biofuel due to laws mandating its use.

Table 1: Model Notation

| Notation | Description |
|---|---|
| $i = \{1, 2\}$ | Commodity (food) and energy crop index, respectively |
| $j = \{W, CP\}$ | Wholesale and capacity procurement contract index, respectively |
| $c_1$ | Marginal cost of commodity crop production (per unit area) |
| $c_2$ | Marginal cost of energy crop production (per unit area) |
| $p$ | Expected spot price (commodity crop) |
| $L$ | Total land (area) available |
| $s$ | Fixed set up cost for energy crop production |
| $L_i$ | Land allocated toward crop $i$ (DV) |
| $\beta_i$ | Maximum yield of crop $i$ per unit area |
| $\delta_i$ | Marginal yield reduction rate of crop $i$ |
| $f_i(L_i)$ | Production function for crop $i$ |
| $y(\tilde{\epsilon})$ | Random fraction of energy crop output realized at harvest (RV) |
| $Q_i(\cdot)$ | Units of crop $i$ available for sale (RV) |
| $g(\cdot)$ | Probability density function (pdf) for yield shock $\tilde{\epsilon}$ |
| $G(\cdot)$ | Cumulative distribution function (cdf) for yield shock $\tilde{\epsilon}$ |
| $\mu$ | Mean (expected) fraction of energy crop output at harvest |
| $\omega$ | Contract price offered by the biorefinery to the farmer (DV) |
| $\alpha$ | Expected retail price of biofuel |
| $k$ | Marginal biofuel production cost |
| $\gamma$ | Biofuel input-output ratio (units biofuel per unit energy crop) |
| $E[\cdot]$ | Expected value operator |
| $L_2^I$ | Optimal land use for energy crop production in the integrated supply chain |
| $L_i^j(\omega)$ | Equilibrium land allocation toward crop $i$ under contract type $j$ at contract price $\omega$ |
| $\omega^j$ | Equilibrium contract price under contract type $j$ |
| $\Pi_B^j(\omega)$ | Biorefinery profit under contract type $j$ at contract price $\omega$ |
| $\Pi_{F'}^j(\omega)$ | Farmer profit from energy crop production under contract type $j$ at contract price $\omega$ |
| $\Pi_{SC}^j(\omega)$ | Decentralized supply chain profit $\left[\Pi_B^j(\omega) + \Pi_{F'}^j(\omega)\right]$ under contract type $j$ at contract price $\omega$ |
| $\Pi^I$ | Integrated supply chain profit |
| $\Pi_F^{NC}$ | Farmer profit from commodity production alone (reservation profit) |

that $E[\Pi^I(L_2^I)]$ is non-negative. The optimal land use for energy crop production described in (3) is the first-best solution for the supply chain. Given anticipated market conditions ($\alpha$), costs ($c_2$ and $k$), the state of technology ($\gamma$, $\beta_2$, and $\delta_2$), and mean energy crop production ($\mu = E[y(\tilde{\epsilon})]$), $L_2^I$ is the profit maximizing land use for energy crop production and $\mu\gamma f_2(L_2^I)$ is the economic optimal (expected) biofuel production level. If the farmer and biorefinery can agree upon terms of trade (contract parameters) which align their individual objectives with those of the integrated system, then the supply chain can achieve optimal performance and we say the decentralized system is coordinated. In other words, the decentralized supply chain which consists of the farmer and biorefinery will be coordinated if the biorefinery's contract terms induce the farmer to allocate the same amount of land toward energy crop production as would be allocated under vertical integration.

Typically, decentralized supply chains act suboptimally due to the double marginalization effect first noted by Spengler [103]. Each firm in the supply chain seeks to maximize the profit earned on products sold downstream, but each firm only considers its own profit maximization problem when making its decisions, as opposed to profit of the entire system. The succession of local profit maximization decisions leads to higher prices, lower quantities and reduced consumer welfare, as compared to an integrated channel where decisions are made to maximize profit of the entire supply chain. In our system, profit maximization and competition between production alternatives drive the discrepancy between local and system optimum behaviors. We make a distinction between system inefficiency due to double marginalization and that resulting from (indirect) competition for the farmer's limited land resource, which we call the commodity market effect. The former is the misalignment between local and global decisions which results from the biorefinery's pricing decision, whereas the latter is the misalignment resulting from the farmer's alternative production opportunities.

In the following sections we analyze wholesale and capacity procurement contracts and evaluate their ability to align the decentralized system's performance with that of the integrated system. Performance is measured by both the land allocated toward energy crop production and the resulting supply chain profit. Our objectives are to understand the factors which enable energy crops to compete with traditional commodity crops for scarce land as well as the effects of competition on contract terms and profit. We seek to answer the following questions: 1) When is the biorefinery willing to offer contract terms which induce the first-best land allocation? 2) What effect does the farmer's outside opportunity (spot market food production) have on the decentralized system's performance? 3) How does the farmer's outside opportunity affect her strength (share of total profits) within the supply chain? and 4) Which contract type is "best" for each agent; and which is best for the system?

### 2.4.2 Willingness to Participate

Before any contracts are proposed, the farmer only produces commodity crops for the spot market. In this business as usual scenario, which we label NC for "no contract," the farmer's land use and profit are respectively,

$$L_1^{NC} \equiv \underset{0 \le L_1 \le L}{\operatorname{argmax}} \; pf_1(L_1) - c_1 L_1 = \min\{L_C, L\} \tag{3}$$

$$E[\Pi_F^{NC}] \equiv pf_1(L_1^{NC}) - c_1 L_1^{NC} \tag{4}$$

where $L_C$ satisfies $f_1'(L_C) = \dfrac{c_1}{p}$.

The farmer is willing to participate in energy crop production (i.e., the farmer accepts the contract) if her expected profit under the stated contractual arrangement with the biorefinery is at least as great as her profit under spot market production only. Therefore, $E[\Pi_F^{NC}]$ is the farmer's reservation profit, or the minimum expected profit she requires in order to grow any energy crops.

### 2.4.3 Wholesale Price Contract

The terms of a wholesale contract require the biorefinery to pay $\omega$ for each unit of biomass produced by the farmer. Since the biorefinery only pays for the units actually produced, the farmer bears much of the risk in production. If the realized biomass yield is low, the farmer not only misses out on the profit that could have been earned by allocating that land toward commodity production, but she also faces direct losses due to the set up and production costs of biomass. We begin our analysis by considering the farmer's response to the biorefinery offering a wholesale price contract to produce energy crops at compensation rate $\omega$ per unit biomass.

*2.4.3.1 Farmer's Problem*

Given she accepts the contract, the farmer's optimal land allocation is the solution to the following problem:

$$E[\Pi_F^W(\omega)] = \max_{\substack{L_1 \geq 0 \\ L_2 \geq 0}} \quad E[\,\omega f_2(L_2) y(\tilde{\epsilon}) + p f_1(L_1) - c_1 L_1 - c_2 L_2 - s\,] \\ \text{s.t.} \quad L_1 + L_2 \leq L \tag{5}$$

**Lemma 1.** *The farmer's objective function is concave in the allocation decision.*

*Proof.* It is straight forward to show that the Hessian matrix for (5) is negative definite. □

**Proposition 1.** *Assuming the land constraint is binding, the farmer's optimal allocation $\{L_1^W, L_2^W\}$ satisfies:*

$$\begin{array}{llll} i) & L_1^W = L, & L_2^W = 0 \;\; if & \mu\omega f_2'(0) - c_2 \leq p f_1'(L) - c_1 \\ ii) & L_1^W = 0, & L_2^W = L \;\; if & \mu\omega f_2'(L) - c_2 \geq p f_1'(0) - c_1 \\ iii) & L_1^W = L - L_2^W, & L_2^W > 0 \;\; if & \mu\omega f_2'(L_2^W) - c_2 = p f_1'(L - L_2^W) - c_1 \end{array}$$

Proposition 1 (Kuhn–Tucker conditions when the Lagrange multiplier is positive) illustrates the relationship between relative profitability of the farmer's production alternatives and optimal land allocation. We ignore result *i*) in which the farmer does not accept the biorefinery's contract. Results *ii*) and *iii*) give the conditions under which the farmer should dedicate some (*iii*), or all (*ii*), of her land toward energy crop production.

In this analysis, and that of subsequent contract types, we restrict our analytical focus to the case in which the farmer's land constraint is binding and it is optimal to allocate only a portion of her land toward biomass production. A binding land constraint means it is optimal for the farmer to grow more commodities and/or biomass, however, she is limited by land availability. We restrict our analysis to this binding case since we are most interested in the potential use of productive cropland for dedicated energy crop production. When considering marginal lands on which commodity production is costly and yields are low, this restriction would not be appropriate. Focusing on the case in which it is optimal to produce both commodity and energy crops allows us to study the important interactions between spot market conditions and contract production, as well as the indirect competition that can occur due to scarcity of the farmer's land resource.

Therefore, concentrating on result *iii*), when offered an acceptable wholesale contract the farmer's optimal land allocation, after substituting our particular production functions, is:

$$\begin{aligned} L_1^W(\omega) &= \frac{p\beta_1 - c_1 + 2\mu\omega\delta_2 L - \mu\omega\beta_2 + c_2}{2(p\delta_1 + \mu\omega\delta_2)} \\ L_2^W(\omega) &= \frac{\mu\omega\beta_2 - c_2 + 2p\delta_1 L - p\beta_1 + c_1}{2(p\delta_1 + \mu\omega\delta_2)} \end{aligned} \tag{6}$$

Land allocated toward energy crop production depends not only on the contract price, production cost and yield uncertainty, but also on the expected spot price and cost of commodity production. Note that the fixed set up cost, $s$, does not affect the land allocation decision. It only affects the farmer's decision of whether or not to accept the contract. The farmer will accept the biorefinery's contract and produce energy crops only if her individual rationality (participation) constraint, $E[\Pi_F^W(\omega)] \geq E[\Pi_F^{NC}]$, is satisfied.

**Corollary 1.** *Ceteris paribus, the equilibrium land allocation is:*

$$L_1^W(\omega) = \begin{cases} \textit{increasing in: } p,\ c_2,\ \beta_1,\ \delta_2,\ \textit{and } L \\ \textit{decreasing in: } \mu,\ \omega,\ c_1,\ \beta_2,\ \textit{and } \delta_1 \end{cases}$$

$$L_2^W(\omega) = \begin{cases} \textit{increasing in: } \mu,\ \omega,\ c_1,\ \beta_2,\ \delta_1,\ \textit{and } L \\ \textit{decreasing in: } p,\ c_2,\ \beta_1,\ \textit{and } \delta_2 \end{cases}$$

As relative profitability of commodity production increases—either through an increase (decrease) in the spot (wholesale) price, or a decrease (increase) in the marginal cost of producing commodities (energy crops)—the farmer's optimal decision is to allocate less land toward biomass production. So, for a fixed contract price, the existence of a commodity market (spot market) tends to further misalign the farmer's objective from that of the integrated system, as compared to the case in which there is only a double marginalization effect. The converse is true when relative profitability of biomass increases. When the biorefinery offers favorable contract terms, or expected biomass yield is high, the farmer prefers to allocate more land toward energy crop production. Note also the role of technology, $\beta_i$ and $\delta_i$, in the farmer's decision; land allocation favors the product with the higher yield. As should be expected, a risk neutral farmer will allocate more land toward the more profitable endeavor.[10] We evaluate the biorefinery's ability to exploit the farmer's land allocation rule in order to secure his desired supply of feedstock.

[10] Comparative static results for $c_1$, $c_2$, $\mu$, $\omega$, $p$, and $L$ hold for any increasing, concave production functions $f_i(L_i)$, not just the particular function considered here. The comparative static results for $\beta_i$ ($\delta_i$), $i = \{1, 2\}$, are a consequence of marginal product increasing (decreasing) with respect to the parameter.

#### 2.4.3.2 *Biorefinery's Problem*

Let $Q_2^W(\omega) \equiv f_2(L_2^W(\omega))y(\tilde{\epsilon})$ be the feedstock supply when the biorefinery offers contract price $\omega$. The biorefinery seeks to maximize expected profit from the sale of biofuel, subject to the farmer accepting his offer to produce the required biomass. To avoid trivial solutions we assume $\gamma(\alpha - k) \geq \omega$.

$$\begin{aligned} E[\Pi_B^W] \; = \; \max_{\omega \geq 0} \quad & E\left[\left(\gamma(\alpha - k) - \omega\right) Q_2^W(\omega)\right] \\ \text{s.t.} \quad & E[\Pi_F^W(\omega)] \; \geq \; E[\Pi_F^{NC}] \end{aligned} \tag{7}$$

Let $\omega(L_2^W)$ denote the farmer's inverse land allocation function;[11] it is the wholesale price which induces the farmer to allocate $L_2^W$ units of land toward energy crop production. The biorefinery can induce his desired (expected) supply of biomass by offering the appropriate wholesale price. For a fixed $\omega < \gamma(\alpha - k)$ the biorefinery's profit is non-decreasing in $Q_2^W$. Therefore, there is no incentive for the biorefinery to breach the contract and purchase less biomass than is actually produced in the event that the farmer realizes an exceptionally high yield.

The farmer's participation constraint is concave in $\omega$ so Kuhn–Tucker (KKT) conditions are not sufficient to guarantee a unique optimal solution to the biorefinery's contract pricing problem (7). However, since $f_2(\cdot)$ is quadratic, if we let $\omega'$ and $\omega''$ denote the solutions to $E[\Pi_F^W(\omega)] = E[\Pi_F^{NC}]$, with $\omega' < \omega''$ and substitute into the farmer's allocation response function (6), we obtain $L_2(\omega') < 0 < L_2(\omega'')$. Since $L_2(\omega)$ is increasing in $\omega$, and $E[\Pi_F^W]$ is increasing in $L_2$, we can replace the problematic participation constraint $E[\Pi_F^W(\omega)] \geq E[\Pi_F^{NC}]$, with a lower bound on the contract price. We denote $\omega_W''$ the farmer's minimum acceptable wholesale price; it is the wholesale price at which energy crops can be added to the crop mix without reducing her total expected profit. Replacing the participation constraint with the

[11] Since $L_2$ is increasing monotonically in $\omega$ the inverse exists.

linear bound, we rewrite the biorefinery's problem as:

$$E[\Pi_B^W] \;=\; \max_{\omega \geq 0} \quad E\left[\left(\gamma(\alpha - k) - \omega\right) Q_2^W(\omega)\right]$$
$$\text{s.t.} \quad \omega \;\geq\; \omega''_W \tag{8}$$

**Lemma 2.** *The biorefinery's expected profit is concave in $\omega$.*

**Proposition 2.** *There is a unique contract price $\omega^W$ which solves the biorefinery's reduced problem* (8). $\omega^W = \max\{\omega_W^*, \omega''_W\}$ *where:*

$$\omega_W^* \;=\; \gamma(\alpha - k) \;-\; f_2(L_2^W(\omega_W^*)) \left[ f_2'\left(L_2^W(\omega_W^*)\right) \frac{\partial L_2^W}{\partial \omega}\bigg|_{\omega_W^*} \right]^{-1} \quad \textit{and,}$$

$\omega''_W$ *is the farmer's minimum acceptable wholesale price*

*Proof.* In substituting the farmer's participation constraint for a (linear) lower bound on the contract price, any contract price satisfying the Kuhn–Tucker maximum conditions will satisfy the Kuhn–Tucker sufficient conditions and be the global maximizer of biorefinery profits. The solution can take one of three forms: an interior, non-binding solution; a boundary solution; or a local solution. The interior solution occurs when the biorefinery's (unconstrained) optimal contract price is strictly larger than the farmer's minimum acceptable contract price. A boundary solution occurs when the (unconstrained) optimal contract price is equal to the minimum acceptable price. Though the constraint holds with equality, it is not binding since the biorefinery cannot earn a higher profit by offering a lower contract price. Lastly, a local solution occurs when the minimum acceptable contract price is binding. In this case, the biorefinery's profit is maximized at a wholesale price less than $\omega''_W$, but the farmer will not accept any contract offering a price lower than $\omega''_W$. Therefore, as long as $\omega''_W \;\leq\; \gamma(\alpha - k)$, the biorefinery will offer the minimum acceptable contract price since he still expects to earn positive profit.

In case of an interior or boundary solution we obtain the equilibrium contract price by solving the biorefinery's unconstrained problem. Setting the biorefinery's marginal profit equal to zero and solving for $\omega$ we obtain the unique solution:

$$\omega_W^* \;=\; \gamma(\alpha-k)\;-\; f_2(L_2^W(\omega_W^*)) \left[ f_2'\left(L_2^W(\omega_W^*)\right) \frac{\partial L_2^W}{\partial \omega}\bigg|_{\omega_W^*} \right]^{-1} \tag{9}$$

Otherwise, when the constraint is binding $\omega^W \;=\; \omega_W''$. $\square$

Our constraint substitution works because of the the specific form of the production function used. However, for a general increasing and concave production function $f_i(\cdot)$, KKT maximum conditions for problem (7) are necessary and sufficient for identifying the global maximum provided one of the following conditions holds:

**Condition 1** $\dfrac{\partial L_2^W}{\partial \omega} \geq \dfrac{2\mu f_2'(L_2^W(\omega))}{pK_1 + \mu\omega K_2}$

where, $K_1 \;=\; -f_1''(L_1^W(\omega)),$ and $K_2 \;=\; -f_2''(L_2^W(\omega))$.

**Condition 2** $E[\Pi_F^W(\omega)]$ is quasiconcave in $\omega$.

Otherwise, the optimal contract price can be found via an exhaustive search over all $\omega$ in the region $[0, \gamma(\alpha-k)]$. See appendix for proof.

**Proposition 3.** *When the farmer's participation constraint is non-binding the biorefinery's marginal cost of procurement is greater than the contract price $\omega_W^*$ but decreasing in the price elasticity of biomass supply.*

*Proof.* Let $\sigma_W \;\equiv\; f_2'\left(L_2^W(\omega)\right) \frac{\partial L_2^W}{\partial \omega} \frac{\omega}{f_2\left(L_2^W(\omega)\right)}$ denote the price elasticity of biomass supply when the farmer allocates $L_2^W(\omega)$ units of land toward energy crop production. Rearranging (9) we obtain,

$$\gamma(\alpha-k) \;=\; \omega_W^* \;+\; f_2(L_2^W(\omega_W^*)) \left[ f_2'\left(L_2^W(\omega_W^*)\right) \frac{\partial L_2^W}{\partial \omega}\bigg|_{\omega_W^*} \right]^{-1} \;=\; \omega_W^* \left[1 + \frac{1}{\sigma_W}\right] \tag{10}$$

The term $\gamma(\alpha-k)$ expresses the return on biofuel production measured in terms of biomass. It is the revenue earned on each unit of biofuel, net of production costs, and adjusted by the fixed input-output ratio so that it is measured in dollars per unit biomass. It reflects the revenue earned on each unit of biomass procured. Since marginal revenue is equal to marginal cost in optimality, the marginal cost of an additional unit of biomass is $\omega_W^* \left[1 + \frac{1}{\sigma_W}\right]$ by (10). Price elasticity of supply is either inelastic ($0 < \sigma < 1$), unitary elastic ($\sigma = 1$), or elastic ($\sigma > 1$). Therefore, the marginal cost of procuring biomass is greater than the price paid for each unit of biomass and decreasing in elasticity.[12] $\square$

The biorefinery's marginal cost reflects both the price paid for a unit of biomass as well as the cost of inducing production of that unit of biomass. The farmer's inverse land allocation curve $\omega(L_2^W)$ is increasing and convex in $L_2^W$ due to diminishing returns. Consequently, inducing more land, and thus additional biomass, becomes increasingly costly for the biorefinery. The biorefinery must offer a higher contract price to induce additional supply, but that higher price must be paid to all units produced, not just the additional units, thus the marginal cost of additional biomass is greater than the wholesale price. However, when supply is elastic, marginal cost is mitigated since the additional biomass induced is greater than the price increase. The implication of this result, which holds for any increasing concave production function $f(\cdot)$, is that a profit maximizing biorefinery facing increasing marginal costs and constant marginal revenue tends to desire less biomass and produce less biofuel.

**Proposition 4.** *The (unconstrained) optimal biofuel production level (integrated system production) is not profitable when the biorefinery must procure biomass feedstock using a wholesale contract.*[13]

*Proof.* Recall that we assume an interior solution with binding constraint for the

[12] Note $\sigma_W \geq 0$ by our assumption that $f_2'(L) > 0$.

[13] *When the integrated system is sufficiently constrained by land availability there are circumstances under which the decentralized supply chain achieves system optimal performance. This issue will be taken up explicitly in §2.5 but for now we assume* $L_2^I = L_I^\star \leq L$.

farmer's problem. Thus, the farmer's first-order condition must satisfy

$$f_2'\left(L_2^W(\omega)\right) = \frac{pf_1'\left(L - L_2^W(\omega)\right) - c_1 + c_2}{\mu\omega} \tag{11a}$$

while the integrated first-order condition satisfies

$$f_2'(L_2^I) = \frac{c_2}{\mu\gamma(\alpha - k)} \tag{11b}$$

For coordination, we require $L_2^W(\omega) = L_2^I$. Since $f_2(L_2)$ is strictly increasing in $L_2$, this implies

$$\frac{pf_1'\left(L - L_2^W(\omega)\right) - c_1 + c_2}{\mu\omega} = \frac{c_2}{\mu\gamma(\alpha - k)}.$$

In order to induce the first-best land allocation the biorefinery must offer the coordinating contract price:

$$\omega_W^I = \frac{\gamma(\alpha - k)\left[pf_1'(L - L_2^I) - c_1 + c_2\right]}{c_2} \tag{12}$$

But the biorefinery would never offer that wholesale price since it leads to negative (expected) profit.

$$\begin{aligned} E[\Pi_B^W] &= \mu[\gamma(\alpha - k) - \omega_W^I]f_2(L_2^I) \\ &= -\mu\gamma(\alpha - k)\left[\frac{pf_1'(L - L_2^I) - c_1}{c_2}\right] f_2(L_2^I) \quad < 0. \end{aligned}$$

Therefore, $\omega^W < \omega_W^I$, $L_2^W(\omega^W) < L_2^I$, and $\mu\gamma f_2(L_2^W) < \mu\gamma f_2(L_2^I)$. □

In our discussion of Corollary 1 we concluded that the existence of a commodity market misaligned integrated and decentralized system performance further than just the double marginalization effect. The proof of Proposition 4, see (12), provides a mathematical representation of the distortion between decentralized and integrated objectives which can be attributed to the farmer's spot market participation. In the farmer's problem, an interior solution with binding constraint implies $pf_1'(L - L_2^I) - c_1 > 0$. As a result, only a contract price *greater* than the (per unit) return on biofuel can induce the integrated land allocation. In other words, the system cannot be coordinated unless the biorefinery operates at a loss.

In the absence of a spot market, or if the farmer's land constraint is not binding (i.e., $pf_1'(L - L_2^I) - c_1 = 0$), the decentralized supply chain *could* overcome the double marginalization effect and achieve coordination, but only if the biorefinery were willing to offer a contract price equal to his net return; i.e., $\omega = \gamma(\alpha - k)$. In which case, the biorefinery would expect to breakeven while the farmer captured all of the supply chain profit. Offering $\omega = \gamma(\alpha - k)$ cannot be an equilibrium, however, since the biorefinery could improve his own profit by decreasing the wholesale price. So while double marginalization alone discourages coordination in the decentralized system, the commodity market makes coordination impossible. Therefore, if the first-best solution is the scale of agricultural participation required to take full advantage of available profit in the market for biofuel, the wholesale contract would not be structured to achieve this level.

So far, we have assumed the farmer's reservation profit does not constrain the biorefinery's choice of contract price. The following theorem illustrates the effect of a binding participation constraint on supply chain performance.

**Theorem 1.** *Let $\omega_W^*$ denote the biorefinery's preferred contract price (i.e., the biorefinery's unconstrained solution).Then, for $\omega_W^* < \widehat{\omega} \leq \gamma(\alpha - k)$:*

*i)* $L_2^W(\omega_W^*) < L_2^W(\widehat{\omega}) < L_2^I$

*ii)* $E[\Pi_F^W(\omega_W^*)] < E[\Pi_F^W(\widehat{\omega})]$

*iii)* $E[\Pi_{SC}^W(\omega_W^*)] < E[\Pi_{SC}^W(\widehat{\omega})] < E[\Pi^I]$

The superscript $I$ denotes the integrated system's optimal outcome (3), the subscript $SC$ denotes supply chain profit, $E[\Pi_{SC}^W(\omega)] = E[\Pi_{F'}^W(\omega)] + E[\Pi_B^W(\omega)]$, and the subscript $F'$ is used to indicate that only the profit earned from energy crop production is included in the supply chain calculation.

*Proof.*

*i)* By Corollary 1, $\omega_W^* < \widehat{\omega}$ implies $L_2^W(\omega_W^*) < L_2^W(\widehat{\omega})$. From first-order conditions in the integrated system we have: $f_2'(L_2^I) = \dfrac{c_2}{\mu\gamma(\alpha - k)}$. First-order conditions from the farmer's problem yields:

$$f_2'\left(L_2^W(\widehat{\omega})\right) = \frac{p(f_1'\left(L - L_2^W(\widehat{\omega})\right) - c_1 + c_2}{\mu\widehat{\omega}}.$$

Since $p(f_1'\left(L - L_2^W(\widehat{\omega})\right) - c_1 > 0$ and $\gamma(\alpha - k) \geq \widehat{\omega}$, $f_2'(L_2^I) < f_2'\left(L_2^W(\widehat{\omega})\right)$; and by concavity of the production function it implies $L_2^W(\widehat{\omega}) < L_2^I$.

*ii)*

$$\begin{aligned}
E[\Pi_F^W(\omega, L_2^W(\omega))] &= \mu\omega f_2(L_2^W(\omega)) + pf_1(L - L_2^W(\omega)) \\
&\quad - c_1(L - L_2^W(\omega)) - c_2 L_2^W(\omega) - s \\
\frac{\partial E[\Pi_F^W(\omega, L_2^W(\omega))]}{\partial\omega} &= \mu\left[\omega f_2'\left(L_2^W(\omega)\right)\frac{\partial L_2^W}{\partial\omega} + f_2\left(L_2^W(\omega)\right)\right] \\
&\quad - pf_1'\left(L - L_2^W(\omega)\right)\frac{\partial L_2^W}{\partial\omega} + c_1\frac{\partial L_2^W}{\partial\omega} - c_2\frac{\partial L_2^W}{\partial\omega} \\
&= \left[\left(\mu\omega f_2'\left(L_2^W(\omega)\right) - c_2\right) - \left(pf_1'\left(L - L_2^W(\omega)\right) - c_1\right)\right]\frac{\partial L_2^W}{\partial\omega} \\
&\quad + \mu f_2(L_2^W(\omega)) \\
&= \mu f_2(L_2^W(\omega)) > 0 \qquad \text{by Proposition 1–}iii)
\end{aligned}$$

Therefore, $\omega_W^* < \widehat{\omega}$ implies $E[\Pi_F^W(\omega_W^*)] < E[\Pi_F^W(\widehat{\omega})]$.

*iii)* Suppose not. Suppose instead, that

$$E[\Pi_{F'}^W(\omega_W^*)] + E[\Pi_B^W(\omega_W^*)] > E[\Pi_{F'}^W(\widehat{\omega})] + E[\Pi_B^W(\widehat{\omega})]$$

then:

$$E[\Pi_B^W(\omega_W^*)] \;-\; E[\Pi_B^W(\widehat{\omega})] > E[\Pi_{F'}^W(\widehat{\omega})] \;-\; E[\Pi_{F'}^W(\omega_W^*)] \tag{13}$$

$$\mu\gamma(\alpha-k)\left[f_2\big(L_2^W(\omega_W^*)\big) - f_2\big(L_2^W(\widehat{\omega})\big)\right] > c_2\left[L_2^W(\omega_W^*) \;-\; L_2^W(\widehat{\omega})\right] \tag{14}$$

$$\frac{f_2\big(L_2^W(\omega_W^*)\big) - f_2\big(L_2^W(\widehat{\omega})\big)}{L_2^W(\omega_W^*) \;-\; L_2^W(\widehat{\omega})} < \frac{c_2}{\mu\gamma(\alpha-k)} \tag{15}$$

The direction of inequality in (15) is reversed owing to $i$). Referring back to the first-order conditions in the integrated system, the inequality in (15) cannot hold since, for any land allocation less than the integrated allocation $L_2^I$, the slope of the production function is greater than $\dfrac{c_2}{\mu\gamma(\alpha-k)}$. Therefore, $E[\Pi_{SC}^W(\omega_W^*)] < E[\Pi_{SC}^W(\widehat{\omega})]$. The proof of $E[\Pi_{SC}^W(\widehat{\omega})] < E[\Pi^I]$ follows similarly. □

In Theorem 1 we see that increasing the contract price improves the decentralized system performance by reducing the double marginalization effect. By inducing greater land allocation, farmer profit increases at the expense of biorefinery profit, but by enough to boost total supply chain profit. Therefore, if the farmer's participation constraint is binding, the system operates at a level closer to that of the integrated channel. Because a binding participation constraint can result from a large fixed set up cost or a large reservation profit ($E[\Pi_F^{NC}]$), the result in Theorem 1 may seem to contradict our previous result that a profitable spot market tends to reduce the amount of land allocated to energy crops (Corollary 1). This apparent contradiction is resolved, however, when we consider biorefinery and farmer response to spot market conditions concurrently.

In determining the contract terms, the biorefinery must account for the farmer's fixed set up cost and opportunity cost if he is to offer a contract the farmer would be willing to accept. The larger the farmer's opportunity cost—e.g., the more profitable the spot market—the higher the contract price has to be to induce participation. But the farmer makes her allocation decision at the margin. Thus, she only considers the contract price, spot price, production costs and marginal yields when deciding how much land to devote to biomass production. Consequently, at the margin the contract price is relatively high, thus inducing greater land allocation toward energy crops. Stated another way, the farmer's reservation profit does not change her land allocation rule, it only dictates whether she will accept the contract or not. So, if her reservation profit forces the biorefinery to offer a higher contract price than that which maximizes his profit, the energy crop allocation will be greater (than if the biorefinery offered his profit maximizing contract price) since $L_2$ is increasing in $\omega$. The farmer benefits from increased revenue due to both a higher wholesale price and more output, while system performance improves since the increase in biomass suply allows for greater biofuel production and sales.

We have shown that under a wholesale contract structure: 1) there are no mutually beneficial contract terms which support the system optimal allocation of land toward energy crop production, hence optimal biofuel production; 2) while coordination is not possible, when the profit outlook in the commodity market is sufficiently optimistic, the biorefinery must sacrifice some of its profit to ensure participation which improves system performance by reducing the double marginalization effect; and 3) the farmer benefits from the improved system performance by capturing a larger share of total supply chain profit.

### 2.4.4 Capacity Procurement Contract

A capacity procurement contract requires the biorefinery to pay $\omega$ for each unit of land allocated toward the production of biomass, as opposed to paying per unit biomass produced as in the wholesale contract. Therefore, regardless of the realized yield, the farmer is guaranteed income in the amount $\omega L_2$; and, essentially all of the production risk is transferred from the farmer to the biorefinery. The DuPont Corp., in partnership with the University of Tennessee, offered sixteen farmers in

Vonore, Tennessee what we call capacity procurement contracts to grow switchgrass for the first pilot-scale cellulosic ethanol biorefinery [63]. The farmers who accepted the contract dedicated a portion of their total land resource toward the production of switchgrass.

In modeling a capacity procurement contract we assume a forced compliance regime (see [22] for a discussion on forced and voluntary compliance in supply chain contracting). If the biorefinery were unable to monitor the farmer's actions, the farmer could accept $\omega$ without making any investments in land preparation, thereby earning something for nothing. The following analysis assumes it is not too costly for the biorefinery to monitor the farmer's actions at the beginning of the period.[14] Therefore, if biomass supply is low at the end of the period, it is a result of the yield shock, not intentional negligence on the part of the farmer.

#### *2.4.4.1 Farmer's Problem*

A farmer faced with a capacity procurement contract seeks to solve the following profit maximization problem:

$$\begin{aligned} E[\Pi_F^{CP}(\omega)] \;=\; \max_{\substack{L_1 \geq 0 \\ L_2 \geq 0}} \quad & E[(\omega - c_2)L_2 + pf_1(L_1) - c_1 L_1 - s] \\ \text{s.t.} \quad & L_1 + L_2 \leq L \end{aligned} \tag{16}$$

The farmer's objective function is concave, and there is a unique allocation which maximizes profit. Provided the capacity procurement price is greater than the marginal cost of production $c_2$ and sufficient to recover the fixed set up cost, the farmer's land constraint will be binding. Again, assuming it is optimal for the farmer to produce both commodity crops and energy crops, her land allocation when offered an

[14]Assume these monitoring costs have been built in to the contract price.

acceptable capacity procurement contract is:[15]

$$
\begin{aligned}
L_1^{CP}(\omega) &= \frac{p\beta_1 - c_1 - \omega + c_2}{2p\delta_1} \\
L_2^{CP}(\omega) &= \frac{2p\delta_1 L + \omega - c_2 - p\beta_1 + c_1}{2p\delta_1}
\end{aligned}
\tag{17}
$$

**Corollary 2.** *Ceteris paribus, the equilibrium land allocation under capacity procurement contract is:*

$$
L_1^{CP}(\omega) = \begin{cases} \textit{increasing in: } \ p, \ c_2, \ \textit{and } \beta_1 \\ \textit{decreasing in: } \ \omega, \ c_1, \ \textit{and } \delta_1 \end{cases}
$$

$$
L_2^{CP}(\omega) = \begin{cases} \textit{increasing in: } \ \omega, \ c_1, \ \delta_1, \ \textit{and } L \\ \textit{decreasing in: } \ p, \ c_2, \ \textit{and } \beta_1 \end{cases}
$$

As with the wholesale contract, the optimal energy crop allocation under the capacity procurement contract structure is increasing in $\omega$, $c_1$, $\delta_1$ and $L$. However, the farmer's allocation decision is now independent of the energy crop's production function and the risks associated with yield. Also, unlike under wholesale contract, the farmer's commodity allocation decision is independent of the total land available. So for a given contract price, the farmer always dedicates $L_1^{CP}$, regardless of her total land availability. This suggests that, from the biorefinery's perspective, capacity procurement contracts may be particularly desirable when dealing with farmers who have a large land endowment.

#### *2.4.4.2 Biorefinery's Problem*

Under capacity procurement contract, the biorefinery assumes all of the production risk. Therefore, he must choose a contract price large enough to encourage farmer

[15]For general increasing and concave production function $f_i(L_i)$, the equilibrium land allocation solves:

$$
\begin{aligned}
f_1'(L_1^{CP}(\omega)) &= \frac{\omega - c_2 + c_1}{p} \\
L_2^{CP}(\omega) &= L - L_1^{CP}(\omega)
\end{aligned}
$$

participation, but low enough to mitigate against the risk of low yield. Let $Q_2^{CP}(\omega) \equiv f_2(L_2^{CP}(\omega))y(\tilde{\epsilon})$ be the biomass supply when offering capacity procurement price $\omega$. The biorefinery chooses the contract price $\omega^{CP}$ which maximizes expected profit

$$\begin{aligned} E[\Pi_B^{CP}] \;=\; \max_{\omega \geq 0} \quad & E[\gamma(\alpha - k)Q_2^{CP}(\omega) - \omega L_2^{CP}(\omega)] \\ \text{s.t.} \quad & E[\Pi_F^{CP}(\omega)] \;\geq\; E[\Pi_F^{NC}] \end{aligned} \tag{18}$$

**Proposition 5.** *i) The biorefinery's profit function is concave in the contract price $\omega$; ii) the unique contract price which maximizes the biorefinery's expected profit is $\omega^{CP} = \max\{\omega^*_{CP}, \omega''_{CP}\}$ where*

$$\omega^*_{CP} \;=\; \mu\gamma(\alpha - k)f_2'\left(L_2^{CP}(\omega^*_{CP})\right) \;-\; L_2^{CP}(\omega^*_{CP})\left[\left.\frac{\partial L_2^{CP}}{\partial \omega}\right|_{\omega^*_{CP}}\right]^{-1} \tag{19}$$

*$\omega''_{CP}$ is the farmer's minimum acceptable contract price*

*Proof.* i) The biorefinery's marginal profit is:

$$\frac{dE[\Pi_B^{CP}]}{d\omega} \;=\; \mu\gamma(\alpha - k)f_2'\left(L_2^{CP}(\omega)\right)\frac{\partial L_2^{CP}(\omega)}{\partial \omega} \;-\; \omega\frac{\partial L_2^{CP}}{\partial \omega} \;-\; L_2^{CP}(\omega) \tag{20}$$

Differentiating marginal profit we obtain:

$$\begin{aligned} \frac{d^2E[\Pi_B^{CP}]}{d\omega^2} \;=\; & \mu\gamma(\alpha - k)\left[f_2'\left(L_2^{CP}(\omega)\right)\left(\frac{\partial^2 L_2^{CP}}{\partial \omega^2}\right) \;+\; f_2''\left(L_2^{CP}(\omega)\right)\left(\frac{\partial L_2^{CP}}{\partial \omega}\right)^2\right] \\ & -\; \omega\frac{\partial^2 L_2^{CP}}{\partial \omega^2} \;-\; 2\frac{\partial L_2^{CP}}{\partial \omega} \end{aligned} \tag{21}$$

Using Corollary 2, the concavity of $f_2(\cdot)$, and the linearity of $L_2^{CP}(\omega)$, (21) simplifies to

$$\frac{d^2E[\Pi_B^{CP}]}{d\omega^2} \;=\; \mu\gamma(\alpha - k)\left[f_2''\left(L_2^{CP}(\omega)\right)\left(\frac{\partial L_2^{CP}}{\partial \omega}\right)^2\right] \;-\; 2\frac{\partial L_2^{CP}}{\partial \omega} \;<\; 0$$

Thus, the biorefinery's expected profit under capacity procurement contract is concave in $\omega$.

ii) As under the wholesale contract structure, the farmer's participation constraint can be replaced by the linear lower bound constraint, $\omega \geq \omega''_{CP}$, so that KKT conditions are necessary and sufficient. Again, there are three possible solutions: an interior solution with non-binding constraint ($\omega^{CP} = \omega^*_{CP} > \omega''_{CP}$); a boundary solution with non-binding constraint ($\omega^{CP} = \omega^*_{CP} = \omega''_{CP}$); and a local solution characterized by the binding constraint ($\omega^{CP} = \omega''_{CP} > \omega^*_{CP}$). When the constraint is non-binding, the optimal contract price $\omega^*_{CP}$ is obtained by setting (20) equal to zero and solving for $\omega$. □

As with the wholesale contract, when the farmer's participation constraint is non-binding the biorefinery's marginal cost of procuring land is greater than the optimal contract price but decreasing in elasticity. Letting $\sigma_{CP} \equiv \frac{\partial L_2^{CP}}{\partial \omega} \frac{\omega}{L_2^{CP}(\omega)}$ denote the price elasticity of energy crop allocation and rearranging (19) we obtain:

$$\mu\gamma(\alpha - k) f_2' \left(L_2^{CP}(\omega^*_{CP})\right) = \omega^*_{CP} \left[1 + \frac{1}{\sigma_{CP}}\right] \tag{22}$$

The term on the left is the expected marginal revenue earned from an additional unit of land, the term on the right is the marginal cost. The relationship indicates the optimal (unconstrained) contract price is conditioned on expected marginal biomass yield, $\mu f_2' \left(L_2^{CP}(\omega^*_{CP})\right)$.

When introducing the capacity procurement contract, we stated the biorefinery bears all of the production risk. And indeed, the farmer's profit maximization problem is independent of the amount of biomass actually produced. But when the farmer's participation constraint is not binding, the biorefinery is able to share some of this production risk by basing contract terms, in part, on expected marginal biomass yield.

**Proposition 6.** *The (unconstrained) optimal biofuel production level is profitable when the biorefinery procures biomass feedstock using a capacity procurement contract provided $\gamma(\alpha - k)$, is sufficiently large.*

*Proof.* See appendix. □

Under the wholesale contract structure we showed that, at best, the biorefinery could expect to break even when offering a coordinating contract. And that best case scenario hinged on the spot market being sufficiently weak. Theorem 6 shows that under the capacity procurement contract structure, coordination is feasible provided biofuel market conditions are sufficiently favorable. We note, however, that while coordination is feasible (both parties receive non-negative profit) it is not an equilibrium outcome since the biorefinery prefers to offer a contract price less than the coordinating price $\omega_{CP}^I$.

When offered a capacity procurement contract, the farmer's allocation decision is linear in the contract price $\omega$. As a result, the inverse supply function is linear, making it less costly for the biorefinery to induce greater energy crop allocation, relative to the wholesale contract scenario in which each additional unit of land allocated is more costly than the previous. Furthermore, because the biorefinery is able to pass on some of the production risk—unlike the farmer under a wholesale contract—he doesn't have to bear the cost of greater allocation alone. Therefore, even though biomass yield is decreasing (due to diminishing returns) while costs increase as the contract price approaches $\omega_{CP}^I$, when the net return is large enough, the biorefinery can still achieve positive profits.

Inducing the system optimal energy crop allocation does, however, lead to substantial reductions in profit for the biorefinery. We use the following to designate the lowest net return such that the coordinating contract ($\omega = \omega_{CP}^I$) is profitable for both the farmer and biorefinery:
$r_{CP} \equiv \inf\{\gamma(\alpha - k) : E[\Pi_B^{CP}(\omega_{CP}^I)] > 0\}$.

**Theorem 2.** *Let $\omega_{CP}^*$ and $\omega_{CP}^I$ denote the biorefinery's optimal (unconstrained) contract price and the contract price which induces coordination, respectively. Then, for $\gamma(\alpha - k) > r_{CP}$ and $\omega_{CP}^* < \widehat{\omega} \leq \omega_{CP}^I$:*

*i)* $L_2^{CP}(\omega_{CP}^*) < L_2^{CP}(\widehat{\omega}) \leq L_2^I$

*ii)* $E[\Pi_{SC}^{CP}(\omega_{CP}^*)] < E[\Pi_{SC}^{CP}(\widehat{\omega})] \leq E[\Pi^I]$

*iii)* $\dfrac{\Pi_{F'}^{CP}(\omega_{CP}^*)}{E[\Pi_{SC}^{CP}(\omega_{CP}^*)]} < \dfrac{\Pi_{F'}^{CP}(\widehat{\omega})}{E[\Pi_{SC}^{CP}(\widehat{\omega})]} \leq \dfrac{\Pi_{F'}^{CP}(\omega_{CP}^I)}{E[\Pi^I]}$

*Proof.*

i) First we show that $L_2^{CP}(\omega_{CP}^*) < L_2^I$. From (20)

$$f_2'(L_2^{CP}(\omega_{CP}^*)) = \frac{\omega_{CP}^* + L_2^{CP}(\omega_{CP}^*)\left[\frac{\partial L_2^{CP}}{\partial \omega}\Big|_{\omega_{CP}^*}\right]^{-1}}{\mu\gamma(\alpha - k)} \quad \text{and}$$

$f_2(L_2^I) = \frac{c_2}{\mu\gamma(\alpha-k)}$. Since $\frac{\partial L_2^{CP}}{\partial \omega} > 0$ (Corollary 2) and $\omega_{CP}^*$ must be greater than $c_2$ if the farmer is to accept the contract, $f_2'(L_2^{CP}(\omega_{CP}^*)) > f_2(L_2^I)$ which implies $L_2^{CP}(\omega_{CP}^*) < L_2^I$. Therefore, again by Corollary 2,
$L_2^{CP}(\omega_{CP}^*) < L_2^{CP}(\widehat{\omega}) \leq L_2^I$.

ii) The proof is similar to that in Theorem 1–*iii*) on page 27.

iii) If

$$\frac{\Pi_{F'}^{CP}(\omega_{CP}^*)}{E[\Pi_{SC}^{CP}(\omega_{CP}^*)]} < \frac{\Pi_{F'}^{CP}(\widehat{\omega})}{E[\Pi_{SC}^{CP}(\widehat{\omega})]}$$

*then,*

$$\Pi_{F'}^{CP}(\omega_{CP}^*)\Big\{\Pi_{F'}^{CP}(\widehat{\omega}) + E[\Pi_B^{CP}(\widehat{\omega})]\Big\} < \Pi_{F'}^{CP}(\widehat{\omega})\Big\{\Pi_{F'}^{CP}(\omega_{CP}^*) + E[\Pi_B^{CP}(\omega_{CP}^*)]\Big\}$$

*and,*

$$\frac{\Pi_{F'}^{CP}(\omega_{CP}^*)}{\Pi_{F'}^{CP}(\widehat{\omega})} < \frac{E[\Pi_B^{CP}(\omega_{CP}^*)]}{E[\Pi_B^{CP}(\widehat{\omega})]}$$

$\Pi_{F'}^{CP}$ is strictly increasing in $\omega$ so $\Pi_{F'}^{CP}(\omega_{CP}^*) < \Pi_{F'}^{CP}(\widehat{\omega})$. By Theorem 6, for $\gamma(\alpha - k) > r_{CP}$, $E[\Pi_B^{CP}(\widehat{\omega})] > 0$. But, since $\omega_{CP}^*$ is optimal for the biorefinery when $\widehat{\omega}$ is feasible, it must be that $E[\Pi_B^{CP}(\widehat{\omega})] < E[\Pi_B^{CP}(\omega_{CP}^*)]$. Therefore,

$$\frac{\Pi_{F'}^{CP}(\omega_{CP}^*)}{\Pi_{F'}^{CP}(\widehat{\omega})} < 1 < \frac{E[\Pi_B^{CP}(\omega_{CP}^*)]}{E[\Pi_B^{CP}(\widehat{\omega})]}$$

and the result holds. The proof for $\dfrac{\Pi_{F'}^{CP}(\widehat{\omega})}{E[\Pi_{SC}^{CP}(\widehat{\omega})]} \leq \dfrac{\Pi_{F'}^{CP}(\omega_{CP}^I)}{E[\Pi^I]}$ follows similarly.

□

In Theorem 2 we see that supply chain profit is increasing in the capacity procurement price but the biorefinery's share is decreasing. The farmer is able to capture an increasing share of total supply chain profit because her revenue is increasing and convex in $\omega$ while her costs only increase linearly. Meanwhile, the biorefinery's costs are increasing and convex but revenue increases at a decreasing rate. So while increasing the contract price can lead to coordination of the supply chain, the biorefinery must sacrifice his own profit in order to do so.

From a managerial perspective, Theorem 2 implies that if a biorefinery is concerned with achieving an ideal (expected) biofuel production level, offering a potential supplier a capacity procurement contract provides the flexibility to balance profit and production goals. If in the short-term it is more important to meet the production goals (e.g., the integrated channel's production level) than it is to achieve maximal profits, then the biorefinery should offer a capacity procurement contract with the coordinating contract price $\omega_{CP}^{I}$, provided expected net return meets the criteria. Otherwise, if profit is more important, the biorefinery should offer $\omega_{CP}^{*}$. It is also interesting to note that the commodity market has less of an effect on system performance under the capacity procurement structure than under the wholesale contract structure, as illustrated by Corollary 2 and Proposition 6.

We have shown that under a capacity procurement contract structure: 1) integrated performance is feasible although not an equilibrium outcome; 2) when the profit outlook in the commodity market is sufficiently optimistic system performance improves; and 3) the farmer benefits from the improved system performance by capturing a larger share of total supply chain profit.

## 2.5 Contract Comparisons

We have presented two contracts in use, or likely to be used, to encourage feedstock production for biofuels. We have found that wholesale contracts do not allow for coordination of the supply chain even when competition from the commodity market is relatively weak. We have also shown that the capacity procurement contract structure allows for flexibility in achieving production level and profit goals since coordination is feasible under certain biofuel market conditions.

Which contract structure is "best"? From the supply chain perspective, the best contract is the most efficient, defined as the ratio of decentralized supply chain profit to integrated supply chain profit [19]. When competition is moderate so that the biorefinery is not constrained by the farmer's minimum profit constraint, then $L_2^{CP}(\omega_{CP}^*) > L_2^W(\omega_W^*)$ if:

$$\frac{\omega_{CP}^* + L_2^{CP}(\omega_{CP}^*)\left[\left.\frac{\partial L_2^{CP}}{\partial \omega}\right|_{\omega_{CP}^*}\right]^{-1}}{\mu\gamma(\alpha - k)} < \frac{f_2(L_2^W(\omega_W^*))\left[\left.\frac{\partial L_2^W}{\partial \omega}\right|_{\omega_W^*}\right]^{-1}}{\gamma(\alpha - k) - \omega_W^*} \tag{23}$$

The expression in (23) does not lend itself to intuitive economic interpretation so we compare the wholesale and capacity procurement contracts using a numerical example. We use corn and switchgrass as representative commodity and energy crops.

Table 2 provides the benchmark parameter values we use in this computational experiment, along with the range of values used in sensitivity analysis of key exogenous variables. The production parameters—$\beta_1$, $\beta_2$, $c_1$, $c_2$, $\gamma^{-1}$, and $k$—reflect annualized estimates for corn and switchgrass obtained from the literature [90]. The commodity price $p$ was obtained from USDA National Agricultural Statistical Service (NASS) data and the expected biofuel price $\alpha$ was derived from recent gasoline prices using the energy equivalence of ethanol and gasoline.

Table 3 presents a snapshot comparison of the wholesale and capacity procurement contracts. Under benchmark conditions the capacity procurement contract is best, offering both the farmer and biorefinery greater expected profits than the wholesale

Table 2: Benchmark Parameter Values

| Parameter | Benchmark Value | | Description | Sensitivity Range |
|---|---|---|---|---|
| $\beta_1$ | 8,655 | $kg/ha$ | Max commodity yield per area | |
| $\beta_2$ | 10,000 | $kg/ha$ | Max energy crop yield per area | [ 5,000, 10,000 ] |
| $\delta_1$ | 0.1 | $kg/ha^2$ | Marginal yield reduction rate (commodity) | |
| $\delta_2$ | 0.05 | $kg/ha^2$ | Marginal yield reduction rate (energy crop) | [ 0.001, 0.3 ] |
| $p$ | 0.14 | $\$/kg$ | Commodity price | [ 0.11, 0.19 ] |
| $c_1$ | 917 | $\$/ha$ | Commodity production cost | |
| $c_2$ | 230 | $\$/ha$ | Energy crop production cost | |
| $L$ | 10,525 | $ha$ | Total available land resource | [ 8,000, 13,000 ] |
| $s$ | 690 | $ | Fixed set up cost (energy crop) | |
| $\mu$ | 80 | % | Expected harvestable output | [ 40, 100 ] |
| $\gamma^{-1}$ | 9.47 | $kg/gal$ | Input-output ratio (energy crop to biofuel) | |
| $\alpha$ | 2.7 | $\$/gal$ | Expected biofuel price | [ 2.35, 3.50 ] |
| $k$ | 2.03 | $\$/gal$ | Marginal biofuel production cost | |

contract. The biorefinery's share of total system profit is slightly greater under wholesale contract than capacity procurement contract. But both contract structures result in a near 50–50 split of expected system profits between the farmer and biorefinery. Since the farmer's minimum acceptable contract price $\omega''$ is not a binding constraint under these benchmark conditions, the biorefinery finds it optimal to share profits in this manner. However, at the optimal contract prices $\omega^*$, the farmer is only willing to allocate approximately half of her land resource toward energy crop production. We note that the integrated system is constrained by the fixed land resource. Biofuel market conditions are such that the available land cannot support the desired scale of biomass production. That the biorefinery finds it optimal to induce only half of the farmer's land resource in such biofuel market conditions suggests that competing with corn (commodity) production is rather costly.

To understand which parameters lead to better system performance and which lead to significant distinctions in performance quality between the two contract types, we utilize sensitivity analysis. As in our analytical analysis, we restrict our attention to the range of values for which the farmer will produce both biomass and food; and the land resource constraint is binding.

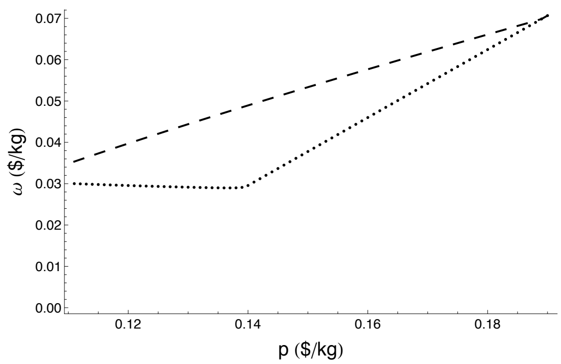
Table 3: Snapshot Comparison of Contract Performance Under Benchmark Conditions

| | | Wholesale | | Capacity Procurement | | Integrated System | |
|---|---|---|---|---|---|---|---|
| Farmer's Min. Price | $\omega''$ | 0.03 | \$/kg | 236 | \$/ha | — | |
| Biorefinery's Preferred Price | $\omega^*$ | 0.05 | \$/kg | 383 | \$/ha | — | |
| Offered Price | $\omega^j = \max\{\omega'', \omega^*\}$ | 0.05 | \$/kg | 383 | \$/ha | — | |
| Land Allocated to Biomass | $L_2(\omega^j)$ | 5,058 | ha | 5,449 | ha | 10,525 | ha |
| Expected Farm Profit | $E[\Pi_{F'}]$ | \$765,819 | | \$830,737 | | — | |
| Expected Biorefinery Profit | $E[\Pi_B]$ | \$860,673 | | \$915,461 | | — | |
| Farmer Share of SC Profit | $E[\Pi_{F'}]/E[\Pi_{SC}]$ | 47 | % | 48 | % | — | |
| Biorefinery Share of SC Profit | $E[\Pi_B]/E[\Pi_{SC}]$ | 53 | % | 52 | % | — | |
| SC Efficiency | $E[\Pi_{SC}]/E[\Pi^I]$ | 50 | % | 54 | % | 100 | % |

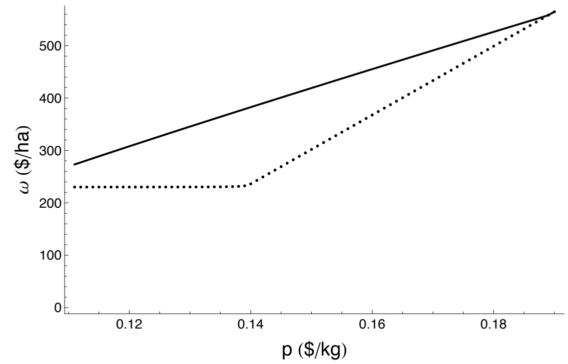
### Commodity (Food) Price Effect

Under benchmark conditions the span of commodity prices at which both the commodity (corn) and energy crop are produced is 8 cents per kg (\$2 per bushel). Figure 2 illustrates the effect of expected commodity price on system performance over that range. Figure 2(a) illustrates the equilibrium wholesale price (dashed line) and minimum acceptable wholesale price (dotted line); while Figure 2(b) illustrates the equilibrium (solid line) and minimum acceptable (dotted line) capacity procurement prices. This convention will be used throughout this section; namely, the dotted line will depict the minimum acceptable contract price, the dashed line will reflect equilibrium outcomes under wholesale contract and the solid line will reflect outcomes under capacity procurement contract.

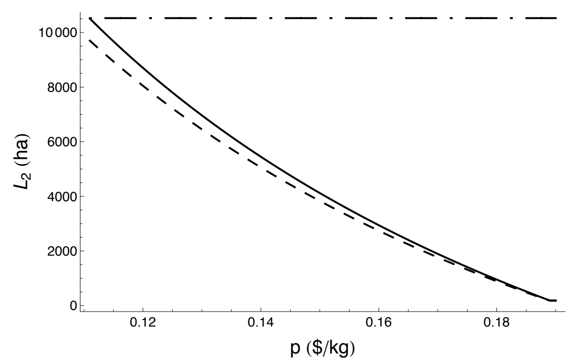
Interestingly, when the price outlook in the commodity market is rather pessimistic (low $p$), so that competition for the farmer's land resource is weak, the biorefinery finds it optimal to pay a small premium to secure the desired biomass feedstock. We refer to the difference between the equilibrium contract price and the minimum acceptable contract price as the "premium." Since all other parameters are left at their benchmark values, this shows that when competition is relatively weak, the biorefinery is willing to pay a premium in order to secure enough feedstock to take




(a) Wholesale Price




(b) Capacity Procurement Price




(c) Energy Crop Allocation

Figure 2: Commodity price effect on equilibrium contract terms and energy crop allocation in the decentralized supply chain. The *dotted* line depicts the farmer's minimum acceptable contract price; the *dashed* line depicts equilibrium outcomes under wholesale contract; the *solid* line depicts equilibrium outcomes under capacity procurement contract; and, the *dot-dashed* line portrays outcomes in the vertically integrated system.

advantage of favorable conditions in the biofuel market. Recall from the snapshot that the integrated system is constrained by the land resource under benchmark conditions in the biofuel market.

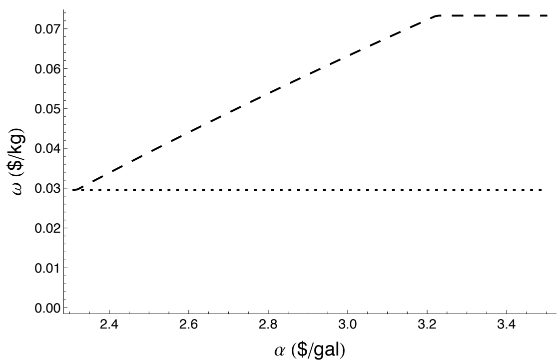
The price premium increases at moderate levels of competition, then decreases as the competition becomes staunch. For $p >$ \$0.14/kg expected commodity market margins are sufficiently high so that the farmer's land resource constrains her desired commodity production level (in the absence of a biomass contract). Therefore, her minimum acceptable contract price increases significantly in this range. Her reluctance to grow energy crops under these commodity market conditions is demonstrated in Figure 2(c).

Though competition from the commodity market is an important factor in system performance, Figure 2 also illustrates the importance of double marginalization. In this sensitivity analysis, all parameters except the expected spot price are held at their benchmark levels. Therefore, the biorefinery can always afford to offer any of the equilibrium prices in Figures 2(a) and 2(b). Offering the highest of those prices would lead to a greater land allocation and thus greater biofuel sales. However, the biorefinery faces a tradeoff between acquiring more biomass—hence selling more biofuel—by offering a higher contract price and earning a higher profit margin on each unit of biomass procured.

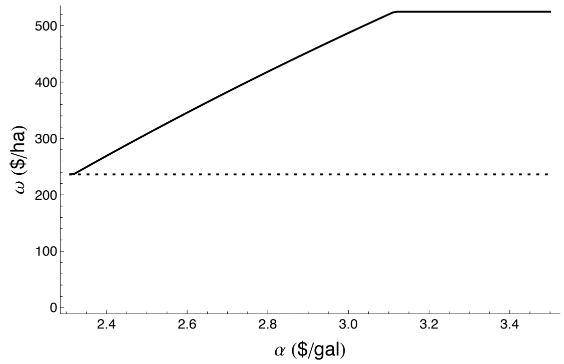
**Biofuel price effect**

Proposition 4 proved that the wholesale contract cannot coordinate the supply chain and Proposition 6 showed that while coordination is feasible under capacity procurement contract for certain biofuel prices, it is not an equilibrium outcome. The results presented in Figure 3 seem to contradict those conclusions. The caveat is those results hold as long as the fixed land resource does not constrain the integrated system too much. With the steep rise in the integrated system's allocation from a small increase in the expected biofuel price $\alpha$, see Figure 3(c), it is evident that when conditions in the biofuel market look promising, the land constraint is significantly binding. The integrated system prefers to allocate substantially more than $L$ units of land toward biomass production.

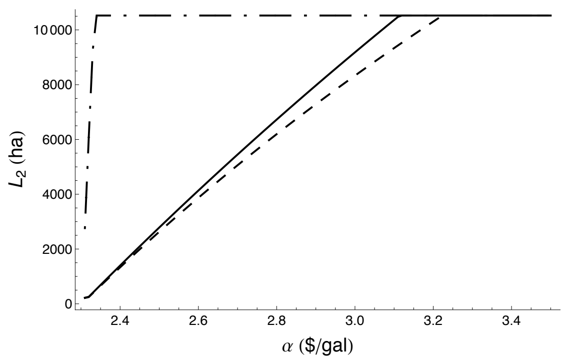
If the land allotment was non-binding for the integrated channel, regardless of how profitable biofuel became, coordination would not be achieved. The integrated system would always prefer to allocate more land toward energy crop production than the biorefinery would be willing to induce. However, as Figures 3(a) and 3(b) demonstrate, the biorefinery offers a significant premium to compete for the farmer's




(a) Wholesale Price




(b) Capacity Procurement Price



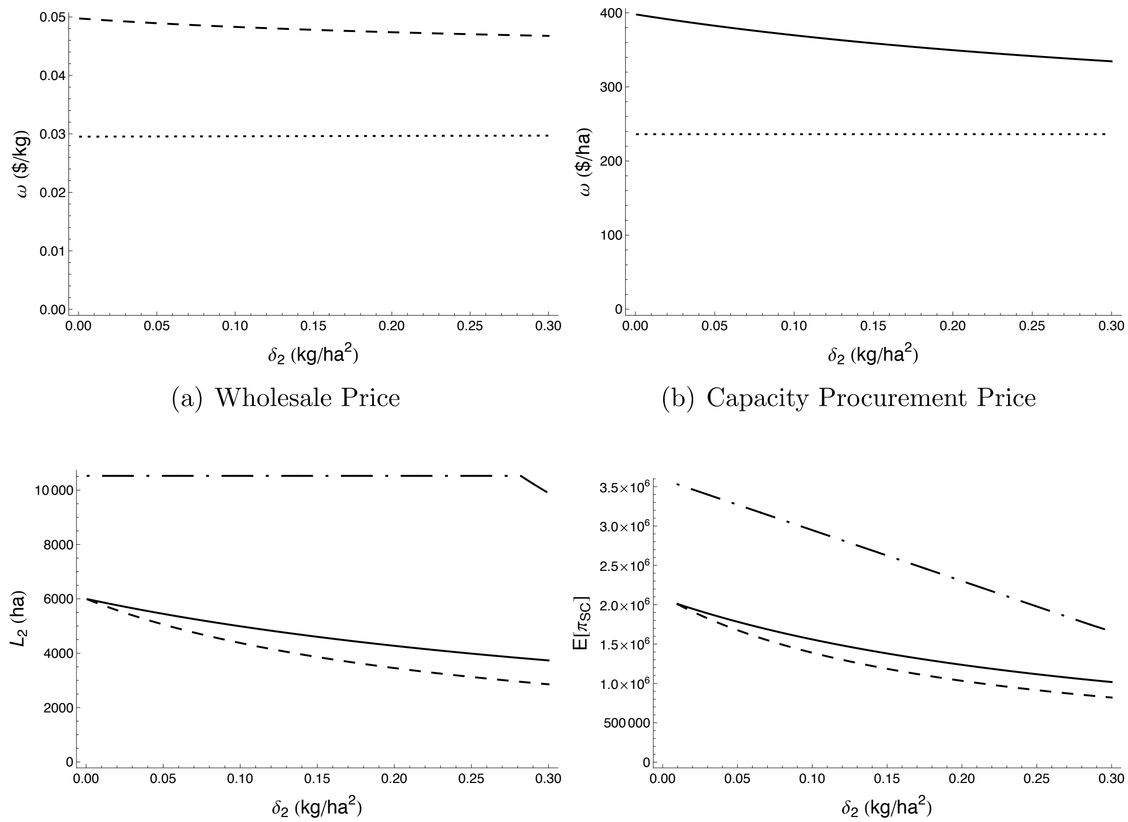

(c) Energy Crop Allocation

Figure 3: Biofuel price effect on equilibrium contract terms and energy crop allocation in the decentralized supply chain. The *dotted* line depicts the farmer's minimum acceptable contract price; the *dashed* line depicts equilibrium outcomes under wholesale contract; the *solid* line depicts equilibrium outcomes under capacity procurement contract; and, the *dot-dashed* line portrays outcomes in the vertically integrated system.

land resource. The equilibrium contract price and premium are increasing in $\alpha$, until the point at which the biorefinery is able to induce the farmer's full land resource for biomass production. Thereafter, the equilibrium contract price is flat; the biorefinery never finds it optimal to unnecessarily share profit by offering a contract price greater than what is needed to induce the farmer's total land resource.

### Marginal (biomass) yield reduction rate effect

The marginal yield reduction rate $\delta_2$, is an important parameter affecting these computational results. We adapted our crop production function from Howitt [58]




(a) Wholesale Price

(b) Capacity Procurement Price

(c) Energy Crop Allocation

(d) Supply Chain Profit

Figure 4: Effect of yield reduction rate (diminishing returns) on equilibrium contract terms and energy crop allocation in the decentralized supply chain. The *dotted* line depicts the farmer's minimum acceptable contract price; the *dashed* line depicts equilibrium outcomes under wholesale contract; the *solid* line depicts equilibrium outcomes under capacity procurement contract; and, the *dot-dashed* line portrays outcomes in the vertically integrated system.

who provides a number of reasons for which linear production technologies with empirically unjustifiable constraints are an inappropriate tool for agricultural practitioners, particularly policy modelers.

> An alternative explanation to linear technologies with constraints is that the profit function is nonlinear in land for most crops, and that the observed crop allocations are a result of a mix of unconstrained and constrained optima. The most common reasons for a decreasing gross margin per acre are declining yields due to heterogeneous land quality, risk

aversion, or increasing costs due to restricted management or machinery capacity [58].

The nonlinear production function employed here reflects the diminishing returns to agricultural production due to heterogeneous land quality. Note, however, that diminishing returns are also typically expected whenever there are capacity constraints. Nevertheless, we evaluate the sensitivity of our model results to this nonlinear assumption.

Note that as $\delta_2 \to 0$ energy crop production approaches linearity so that there are constant returns to energy crop production. The sensitivity analysis depicted in Figure 4 shows that even when $\delta_1 > 0$—the commodity margin per hectacre is declining—near constant returns to energy crop production (as $\delta_2 \to 0$) does not result in a complete departure from commodity crop production, see Figure 4(c), provided there are moderate profits in the commodity market. In this case, the (fixed) expected biofuel price limits the biorefinery's desire to compete for the farmer's land resource.

The equilibrium wholesale and capacity procurement prices are decreasing slightly in $\delta_2$. The farmer's minimum acceptable wholesale price is increasing slightly in $\delta_2$ while the minimum acceptable capacity procurement price is unaffected by $\delta_2$. This explains the slight divergence in performance between the two contracts as depicted in Figures 4(c) and 4(d).

The biorefinery pays a sizable premium under both contract structures to remain competitive with commodity crop production. Despite the premium, however, biomass allocation in the decentralized supply chain pales in comparison to that in the integrated channel. Note from Figure 4(d) that profit in the vertically integrated channel is decreasing in $\delta_2$ at a much faster rate than in the decentralized supply chains. This suggests that while competition has an important effect on the land allocated toward energy crops, it has less of an impact on system profit when biomass productivity is low.

## 2.6 Conclusions

This analysis considers the economic optimal biomass land allocation—and expected biofuel production—in a given area based on anticipated biofuel market conditions, production costs and yield uncertainty, as well as the allocation (and production) achieved when a profit maximizing biorefinery contracts with a profit maximizing farmer who has alternative production options. We have considered two contract structures, a wholesale contract in which the farmer is only paid for the biomass actually produced, and a capacity procurement contract in which the farmer is paid per unit land allocated to biomass production, regardless of the actual output. While the two contracts differ substantially in structure, the difference in performance was not substantial in the computational experiments conducted. This analysis assumed a risk neutral farmer and biorefinery since farms in the US that produce under contract tend to be considerably larger than those that do not [75]. Explicitly considering risk aversion could lead to marked differences in performance between the two structures.

In general, the wholesale contract performed worse than the capacity procurement contract in terms of land allocated toward energy crop production and total supply chain profit. One potential explanation is the double incidence of risk experienced under wholesale contract. Since we have not imposed explicit capacity utilization requirements on the biorefinery, most of the production risk falls on the farmer and is reflected in her land allocation decision. However, the biorefinery accounts for the yield uncertainty indirectly when making his pricing decision since the realized biomass yield effects his biofuel production level. In contrast, under capacity procurement contract the farmer bears none of the production risk directly. The biorefinery is able to share this risk though, via the offered contract price. Another explanation is the reduced effect of commodity market competition under capacity procurement contract as illustrated by Corollary 2 and Proposition 6.

While the capacity procurement contract outperformed the wholesale contract, neither was able to achieve the supply chain optimal energy crop allocation (and expected biofuel production level), except when the fixed land constraint was severely constraining to the system. The farmer's commodity market alternative and double marginalization both contribute to this failure. Under wholesale contract we found that achieving the supply chain optimal allocation is impossible provided there are at least modest margins in the commodity market. But even when commodity margins are thin, the supply chain optimal energy crop allocation is only possible if the biorefinery is willing to operate at zero profit. A similar result holds under capacity procurement contract as well; except there is a certain level of revenue in the biofuel market at which the supply chain optimal energy crop allocation is profitable for both parties but suboptimal for the biorefinery. As mentioned previously, the integrated system's energy crop allocation represents the economic optimal production level given biofuel market conditions. Therefore, this result suggests that in the event that there are substantial profits in the biofuel market (e.g. due to high oil/gasoline prices), commodity crop production may not be completely threatened by contracts which bid away cropland.

We presented the impact of three key factors on performance: commodity price, biofuel price, and marginal yield reduction rate. In general, the land allocated to energy crop production is decreasing in the commodity price. However, when the farmer expects substantial profit from commodity production, so that her reservation profit is a binding constraint for the biorefinery, the biorefinery must sacrifice some of its profits via higher contract prices, in order to gain farmer participation. This reduction in double marginalization leads to a greater energy crop allocation and system profit.

In light of commodity market competition and double marginalization, the biofuel price is the most important factor affecting feedstock supply; it will play an important role in overcoming the feedstock acquisition challenge. On one hand, the biofuel price, which is driven by the price of oil, is the biggest threat to commodity crop production. At higher biofuel prices, the biorefinery is willing and able to offer the farmer price premiums substantial enough to divert a significant amount of land away from commodity production. On the other hand, however, for geopolitical reasons it is the most difficult parameter to predict. Therefore, the biorefinery's confidence in the expected biofuel price, especially over long periods of time, will be essential to establishing a viable industry for next-generation biofuels. Even more vital than improving energy crop yields, reducing uncertainty in energy crop production, or increasing the supply of land available for energy crop production (see the sensitivity analysis on $\beta_2$ (maximum yield), $\mu$ (expected fraction of yield realized at harvest), and $L$ (total land availability), in the appendix to this chapter.)

In varying the marginal yield reduction rate—which captures diminishing returns to production due to heterogeneous land quality, risk aversion, etc.—we demonstrated that the biorefinery's ability to compete with the commodity market was indeed the primary driver of model results, not the specific form of our production function. We show that even when energy crop production is particularly favorable ($\delta_2 \to 0$), modest competition from the commodity market can temper drastic changes to the agricultural landscape; a point that is very important in the food versus fuel debate.

## 2.7 *Appendix*

### 2.7.1 Sufficiency Conditions for Proposition 2

For general increasing and concave production functions $f_i(L_i)$, KKT maximum conditions for problem (7) are necessary and sufficient for identifying the global maximum provided:

**Condition 1** $\dfrac{\partial L_2^W}{\partial \omega} \geq \dfrac{2\mu f_2'(L_2^W(\omega))}{pK_1 + \mu\omega K_2}$

where, $K_1 = -f_1''(L_1^W(\omega))$, and $K_2 = -f_2''(L_2^W(\omega))$.

**Condition 2** $E[\Pi_F^W(\omega)]$ is quasiconcave in $\omega$.

Because the biorefinery's expected profit $E[\Pi_B^W]$ is concave in $\omega$, Kuhn–Tucker Sufficiency conditions are satisfied as long as $E[\Pi_F^W(\omega)]$ is concave in $\omega$. We use $L_i^W$ as shorthand notation for $L_i^W(\omega)$.

$$\frac{dE[\Pi_F^W(\omega)]}{d\omega} = pf_1'(L_1^W)\frac{\partial L_1^W}{\partial \omega} + \mu\left[\omega f_2'(L_2^W)\frac{\partial L_2^W}{\partial \omega} + f_2(L_2^W)\right] - c_1\frac{\partial L_1^W}{\partial \omega} - c_2\frac{\partial L_2^W}{\partial \omega}$$

$\frac{\partial L_1^W}{\partial \omega} = -\frac{\partial L_2^W}{\partial \omega}$ due to the farmer's land constraint holding with equality at the optimal solution, $L_1^W + L_2^W = L$.

$$\begin{aligned}\frac{d^2E[\Pi_F^W(\omega)]}{d\omega^2} &= \left[\mu\omega f_2'(L_2^W) - c_2\right]\frac{\partial^2 L_2^W}{\partial \omega^2} - \left[pf_1'(L_1^W) - c_1\right]\frac{\partial^2 L_2^W}{\partial \omega^2} + pf_1''(L_1^W)\Big(\frac{\partial L_2^W}{\partial \omega}\Big)^2 \\ &\quad + \mu\omega f_2''(L_2^W)\Big(\frac{\partial L_2^W}{\partial \omega}\Big)^2 + 2\mu f_2'(L_2^W)\frac{\partial L_2^W}{\partial \omega} \end{aligned} \tag{24}$$

$$\begin{aligned} &= \underbrace{\left\{\left[\mu\omega f_2'(L_2^W) - c_2\right] - \left[pf_1'(L_1^W) - c_1\right]\right\}}_{A}\frac{\partial^2 L_2^W}{\partial \omega^2} + pf_1''(L_1^W)\Big(\frac{\partial L_2^W}{\partial \omega}\Big)^2 \\ &\quad + \mu\omega f_2''(L_2^W)\Big(\frac{\partial L_2^W}{\partial \omega}\Big)^2 + 2\mu f_2'(L_2^W)\frac{\partial L_2^W}{\partial \omega} \end{aligned} \tag{25}$$

$A = 0$ by Proposition 1-*iii*). Therefore, $E[\Pi_F^W(\omega)]$ is concave in $\omega$ provided:

$$pf_1''(L_1^W)\Big(\frac{\partial L_2^W}{\partial \omega}\Big)^2 + \mu\omega f_2''(L_2^W)\Big(\frac{\partial L_2^W}{\partial \omega}\Big)^2 + 2\mu f_2'(L_2^W)\frac{\partial L_2^W}{\partial \omega} \leq 0$$

or,

$$\frac{\partial L_2^W}{\partial \omega} \geq \frac{2\mu f_2'(L_2^W(\omega))}{pK_1 + \mu\omega K_2}$$

Since $E[\Pi_B^W]$ is concave in $\omega$, Arrow–Enthoven Sufficiency conditions are satisfied as long as $E[\Pi_F^W(\omega)]$ is quasiconcave in $\omega$. □

### 2.7.2 Proof of Proposition 6

For a general increasing, concave production function $f_i(L_i)$ let $\omega_{CP}^I$ be the price per area which solves $L_2^{CP}(\omega) = L_2^I$. First-order conditions from the farmer's land allocation problem, assuming binding constraint, require

$$\omega - c_2 = pf_1'(L - L_2^{CP}(\omega)) - c_1.$$

Thus,

$$\omega_{CP}^I = pf_1'(L - L_2^I) - c_1 + c_2.$$

The optimal biofuel production level is profitable for the biorefinery provided:

$$E[\Pi_B(\omega_{CP}^I)] = \mu\gamma(\alpha - k)f_2(L_2^I) - \omega_{CP}^I L_2^I > 0$$

Substituting $\omega_{CP}^I$ and subtracting $(c_2 L_2^I + s)$ from both sides:

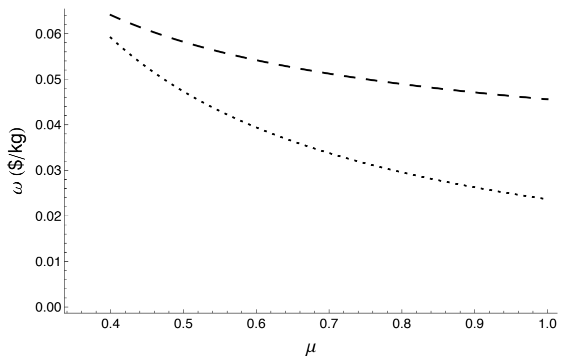
$$\mu\gamma(\alpha - k)f_2(L_2^I) > \Big[pf_1'(L - L_2^I) - c_1 + c_2\Big]L_2^I \tag{26}$$

$$\underbrace{\mu\gamma(\alpha - k)f_2(L_2^I) - c_2 L_2^I - s}_{X} > \underbrace{\Big[pf_1'(L - L_2^I) - c_1\Big]L_2^I - s}_{Y} \tag{27}$$

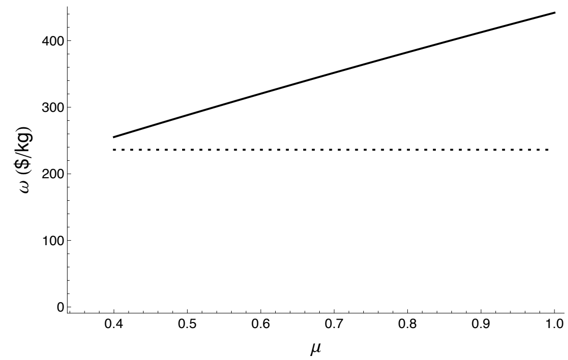
By the envelope theorem, $X$ (the vertically integrated channel's optimal value function) is strictly increasing in $\gamma(\alpha - k)$. $Y$ is also increasing in $\gamma(\alpha - k)$ but is bounded above by $[pf_1'(0) - c_1]L - s$. Therefore, there exists $\gamma(\alpha - k)$ such that $X > Y$. Denote $r_{CP} \equiv \inf\{\gamma(\alpha - k) : E[\Pi_B^{CP}(\omega_{CP}^I)] > 0\}$. The (unconstrained) optimal biofuel production level is profitable provided $\omega_{CP}^I\Big|_{\gamma(\alpha-k)\geq r_{CP}} \geq \omega_{CP}''$.

### 2.7.3 Sensitivity Analysis

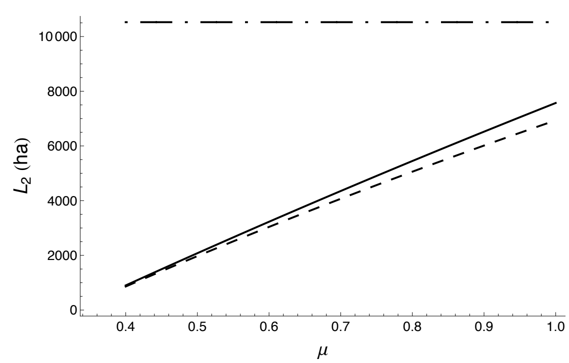
**Mean Harvestable Output Effect**




(a) Wholesale Price




(b) Capacity Procurement Price

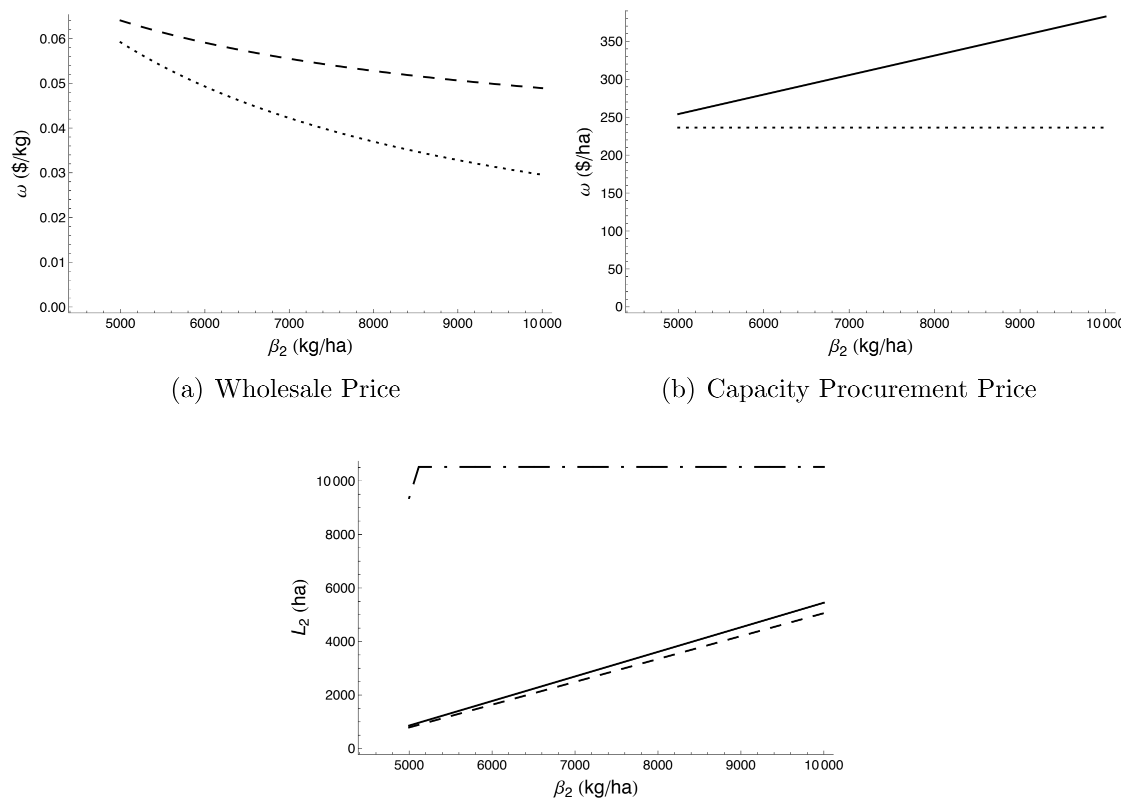



(c) Energy Crop Allocation

Figure 5: Effect of mean harvestable output on equilibrium contract terms and energy crop allocation in the decentralized supply chain. The *dotted* line depicts the farmer's minimum acceptable contract price; the *dashed* line depicts equilibrium outcomes under wholesale contract; the *solid* line depicts equilibrium outcomes under capacity procurement contract; and, the *dot-dashed* line portrays outcomes in the vertically integrated system.

As uncertainty in energy crop production decreases ($\mu$ increases) the premium increases, but the effect on equilibrium contract pricing varies by contract structure. Under wholesale contract, where the farmer bears much of the production risk, the equilibrium price is decreasing. However, under capacity procurement contract, where the farmer is not directly effected by actual yields, the equilibrium price is increasing. Under capacity procurement, the biorefinery can only take advantage of favorable biomass yields by offering a higher price to induce greater land allocation. A similar relationship is exhibited as the biomass yield increases, see Figure 6.

### Maximum (biomass) yield effect



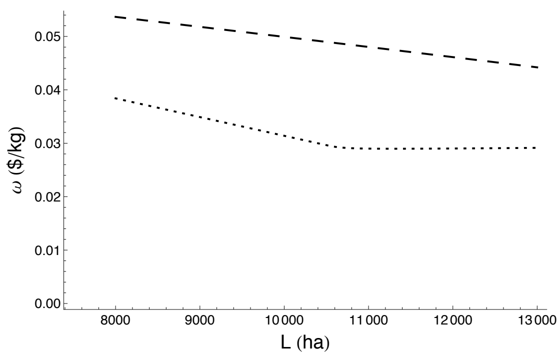

(a) Wholesale Price

(b) Capacity Procurement Price

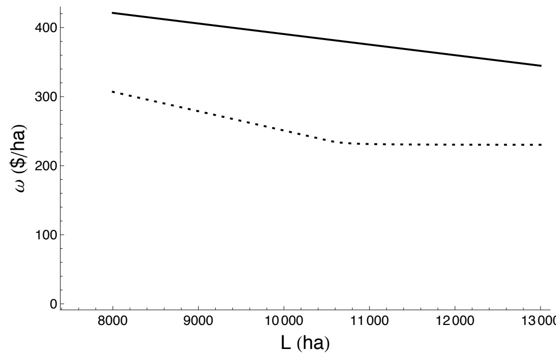
(c) Energy Crop Allocation

Figure 6: Effect of maximum (biomass) yield on equilibrium contract terms and energy crop allocation in the decentralized supply chain. The *dotted* line depicts the farmer's minimum acceptable contract price; the *dashed* line depicts equilibrium outcomes under wholesale contract; the *solid* line depicts equilibrium outcomes under capacity procurement contract; and, the *dot-dashed* line portrays outcomes in the vertically integrated system.

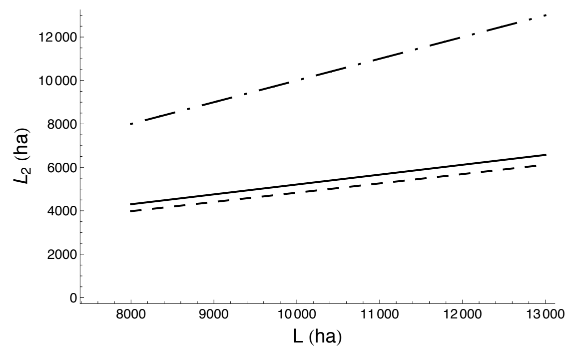
**Available land resource effect**




(a) Wholesale Price




(b) Capacity Procurement Price




(c) Energy Crop Allocation

Figure 7: Effect of total land available on equilibrium contract terms and energy crop allocation in the decentralized supply chain. The *dotted* line depicts the farmer's minimum acceptable contract price; the *dashed* line depicts equilibrium outcomes under wholesale contract; the *solid* line depicts equilibrium outcomes under capacity procurement contract; and, the *dot-dashed* line portrays outcomes in the vertically integrated system.

The reduction in equilibrium contract prices as the farmer's total supply of land increases illustrates the importance of the biorefinery's profit motives. From Figures 7(a) and 7(b) it is clear that the biorefinery can afford to pay higher contract prices when the farmer's land resource is larger, but he prefers not too. As a result, see Figure 7(c), the farmer only allocates a (decreasing) fraction of the land that is allocated under vertical integration.

# CHAPTER III

# COMMODITY MARKET EFFECTS

## *3.1 Introduction*

In the previous chapter we presented a model which illustrated the design of two different contract structures with the goal of securing biomass feedstock for biofuel production. Results from the model indicated the importance of competition for the farmer's land resource on equilibrium contract terms and performance in the biofuel supply chain. This source of competition was the commodity market. Despite being able to directly influence a farmer's participation in energy crop production, via the contract terms offered, moderate margins in the commodity market left the biorefinery with an important tradeoff: offer more competitive contract terms to secure more feedstock and produce more biofuel, or maximize the profit margin from each unit of biomass procured.

Economic feasibility studies have been important in the analysis of biofuel and bioenergy policy. Since next-generation biofuels are not yet available commercially, many analyses rely on cost estimates in assessing the viability of various bioenergy feedstocks. After accounting for the total costs of producing the feedstock, including the opportunity cost of producing other crops or the next best use of land, these breakeven models conclude that biomass feedstock production is viable if agricultural producers receive prices that cover these costs. As demonstrated in Chapter 2, competition for scarce land is an important driver of potential biomass supply. However, competition is only implicitly considered in the breakeven pricing method via the opportunity cost. Moreover, the breakeven approach implicitly assumes that when offered a price greater than the breakeven price, the farmer should specialize in the production of that crop, or make it the dominant production activity. When applied to the production of dedicated energy crops, analyses that employ breakeven pricing also include an arbitrary limit to how much land would be used (i.e., how dominant the crop would be) in order to reflect market uncertainties. However, contracting will reduce the market uncertainty for farmers by making payment agreements legally binding; thus, the manner in which farmers choose to adopt energy crop production will have an important effect on a biorefinery's contract pricing strategy.

The analysis conducted in Chapter 2 assumes that energy crops will be added to a farmer's crop mix provided it doesn't reduce expected profitability of the entire farm operation. Its relative importance in the crop mix depended on the biorefinery's contract price. In contrast, the breakeven pricing approach assumes that energy crops will be adopted if their production is at least as profitable as commodity crop production and implicitly assumes that it will be the dominant or specialized crop. It is unlikely that in the near term farmers would make energy crop production a dominant activity since the next-generation biofuel industry is marred with so much uncertainty. However, surveys of farmers who engage in contracting of field crops suggest there may be a time at which some farmers are willing to specialize in energy crop production.

> Among corn, soybean, and wheat operations that used contracts, over 60 percent put between 20 and 60 percent of production under contract. Many farms, however, fell outside that range: some put all of their production under contract, and surprisingly large numbers put either a high share (81–100 percent of production) or a low share (1–20 percent) under contract [76].

The assumptions made about how farmers will adopt energy crop production under contract (i.e., incorporating it into the crop mix versus specializing) has important implications for how contracts should be designed to secure feedstock.

In this chapter, we compare performance in the biofuel supply chain (the biorefinery's pricing strategy, and the farmer's corresponding land allocation/biomass supply) when contracting with a farmer who will include energy crop production as part of a diversified crop mix, as developed in Chapter 2, with performance in a supply chain in which a farmer is assumed to specialize in energy crop production, as implied by the breakeven pricing approach. A farmer who specializes in energy crop production is assumed to maximize profit from energy crop production, provided it is at least as profitable as commodity production. Any land not used in energy crop production will then be put toward commodity crop production or some other use. The comparison will aid in quantifying the explicit impact of commodity market conditions on energy crop (and biofuel) production.

## 3.2 Literature Review

Contracting for supply in this specialized case yields results similar to those found in the supply chain literature under contracting in buyer-driven channels. In a buyer-driven system, buyers assert their dominance by dictating their desired mark-up over the supplier's stated wholesale price or by setting contract terms directly.[1] We limit the scope of this review to the literature in which buyers determine contract parameters as it is more directly in line with the work conducted in this analysis, as well as what is relevant in the context of agricultural contracting. For work in the alternate stream—where the supplier maintains her traditional wholesale price setting role, albeit in response to the dominant buyer's mark-up specification or some other condition—see Choi [25], Ertek and Griffin [38], Lau et al. [69] and Liu and Cetinkaya [71].

Cachon and Lariviere [22] were among the first to consider a buyer-driven channel

[1] The grocery channel and Walmart are common examples of buyer-driven supply chains.

in which the buyer determines contract terms. In their study of capacity procurement under both forced and voluntary compliance, as well as full and asymmetric information with regard to demand forecasts, their analysis focuses on contract terms which specify quantities of firm commitments and options. In the full information case, when compliance is forced no firm commitments are made and the option and exercise prices are chosen such that the supplier receives her minimum required profit and the buyer extracts all excess system profit. When compliance is voluntary, the buyer purchases neither firm commitments nor options so that the interaction is reduced to a wholesale (price-only) contract. Cachon and Lariviere do not determine the equilibrium wholesale price; however, they demonstrate that it depends largely on the variability of demand. When information is asymmetric and compliance is forced, the buyer can credibly signal his demand forecast without cost so that, again, the equilibrium option and exercise price leaves the supplier with her minimum required profit and the buyer with all of the excess supply chain profit. In contrast, under voluntary compliance, the buyer who expects high demand incurs a cost in signaling the demand forecast because he must induce a capacity investment greater than that under full information.

Ferguson [46] investigates contract pricing when commitments are made early or delayed, under various leadership structures, including the dominant buyer structure. In this two period model the buyer can commit early by submitting orders before the supplier builds capacity, or delay commitment by submitting orders after the supplier has built capacity. In the former, the supplier's profit is deterministic, while in the latter she is subject to the uncertainty in demand for the buyer's product. When the buyer is dominant, Ferguson finds that with early commitment the contract price offered is just sufficient to cover the supplier's reservation profit allowing the buyer to extract all excess system profit. However, under delayed commitment the buyer must induce greater capacity investment using a higher contract price so that the supplier's expected profit meets her reservation level.

Ferguson's early commitment case is analogous to the full information, forced compliance case in [22]. When the supplier's profit is deterministic in a buyer-driven channel, the buyer can extract all system profit above the supplier's minimum requirement. However, in our model, even with the assumption of multiplicative supply risk which degenerates to a deterministic model under risk neutrality in which random variables are replaced with their expected values, there are conditions under which the buyer offers a wholesale price which affords the supplier profits in excess of her minimal requirement. Due to diminishing returns (marginal yield reduction rate), the wholesale price that equates the supplier's profit to her reservation level is not always profit maximizing for the buyer. The problem is even more pronounced when the supplier's capacity is limited and there is an alternative endeavor competing for that same resource. The implication is that the supplier in our model is granted a degree of market power by the contractual arrangement.

Wang and Gerchak [123] model the "assembler-as-leader" game in which an assembler offers multiple suppliers a wholesale contract to encourage capacity installation for later production of the components needed to assemble a final good whose demand is uncertain at the time of capacity installation. Each firm has a second capacity source so the system is only constrained when one or more of the supplier's is offered a contract price lower than the cost of using the more expensive second capacity source. In which case, the system's capacity is constrained to the minimum of the installed capacity of those suppliers unable to utilize the second source. The assembler (dominant buyer) in this case uses the contract price as a strategic instrument to coordinate the capacity decisions of all the component suppliers in as much as a fixed total payment is allocated so that no supplier is incentivized to install capacity greater than the minimum of all other installed capacities. Gerchak and Wang [49] consider a similar assembly problem using revenue sharing contract schemes. This is in contrast to our model in which a dominant buyer uses contract terms to bid capacity away from a supplier's alternative uses for that capacity.

Capacity reservation contracts, which are common in the semiconductor industry, are like options contracts in that the buyer pays a deductible fee up front for capacity he would like to use in the future and the fee paid on capacity that is never used is non-refundable [37]. This contract structure is similar in spirit to the capacity procurement contract considered here. However, with a capacity procurement contract, the buyer pays for capacity up front and retains the rights to the full production capability of the reserved capacity. We are not aware of any papers which consider capacity reservation contracts in a buyer-driven supply chain. See [125] for a review.

The aforementioned papers consider capacity acquisition; contract terms are designed to induce adequate levels of capacity installation. However, integral to the problem studied here is the supplier's capacity allocation decision in response to contract terms. The supply chain management community has typically covered the capacity allocation problem in the context of a supplier who must allocate fixed capacity used to produce a single good among multiple retailers (buyers). Cachon and Lariviere study various allocation mechanisms according to their impact on supply chain performance in [20] and [21].

We consider a supplier who allocates capacity among heterogeneous products. This distinction is important, especially when capacity is fixed and cannot be adjusted, because the supply chain for one product is indirectly affected by the market for the supplier's other products. When the supplier allocates a homogeneous product between retailers, only the ability to get the "right" amount of product to each retailer affects system performance. When allocating capacity across heterogeneous products, however, whether a particular product is allocated the "right" amount of capacity or not depends on conditions in the markets of all other products, since together they determine how the supplier will allocate capacity. In our biofuels context, the previous chapter illustrated the affect commodity market production had on the supply chain for biofuel.

The operations management community has considered the capacity allocation problem primarily in the context of production and inventory management (e.g. [40, 50, 30]), or flexible resource investment (e.g. [47, 117, 107]). Both streams consider capacity allocation among multiple heterogenous products with uncertain demand. The former determines optimal production and inventory policies for each good when total production is constrained by a shared but limited resource. The latter considers optimal investment in expensive flexible capacity—which can produce multiple heterogenous products, unlike dedicated capacity—as a hedge against demand uncertainty. After demand uncertainty is resolved, the flex capacity is allocated toward various goods according to demand and/or profit contribution. However, neither stream considers a buyer offering a contract in order to influence its allocation of capacity, as we do here.

Like the production and inventory management literature we consider the allocation of a fixed resource among heterogenous goods. However, our focus is on the design of contract terms to influence this allocation. And while capacity allocation is a recourse decision in the flexible resource literature, contrary to what is feasible in the context of our model, the fixed capacity levels in those models are determined endogenously.

Our work departs from the literature in several ways. Paramount is our analysis of contract design in a buyer-driven supply chain with a capacitated, multi-product supplier. Another major distinction is our departure from the standard linear production assumption to include production with decreasing returns. We do not consider demand uncertainty with respect to biofuel sales or commodity sales. Both the supplier (farmer) and manufacturer (biorefinery) are price-takers in their respective markets, thus, in the economic sense both operate as competitive firms in the marketplace;

see [77] for more on competitive markets. As such, both the farmer and biorefinery believe they can sell everything produced at the fixed market price. As in Chapter 2 we assume energy crop production is subject to an idiosyncratic risk that is independent of the land (capacity) allocated toward production. However, without loss of generality, we assume the yield risk is multiplicative so that under risk neutral assumptions, the supply of biomass is adequately characterized by its expected value at the given land allocation.

The farmer's problem is straight forward; she allocates land in order to maximize expected profit. Of primary interest here is the effect of competition on the farmer's land allocation rule and its impact on equilibrium contract terms. We study this via the decisions made when a farmer is assumed to completely adopt production of a contracted good provided her reservation profit is met, versus the assumption that a farmer will add production of the contracted good to her crop mix provided she doesn't expect to earn a lower profit than if she did not. When land is relatively scarce (capacity is tight), the explicit competition from commodity production that exists with a farmer who adds the contracted crop to her crop mix confers an additional degree of market power on the farmer, above the typical reservation profit assumption, which significantly alters the biorefinery's pricing decision.

## *3.3 Model Framework*

### 3.3.1 Model Notation

For easy reference, we reproduce the model framework developed in Chapter 2 here. We consider a two-echelon biofuel supply chain. Downstream is a biorefinery who requires biomass feedstock in order to produce next-generation biofuels. Upstream is a farmer with fixed land resource $L$ which can be used to produce commodity crops for sale on the spot market, energy crops for sale under contract, or both.

The farmer incurs a cost $c_i$, $i = \{1, 2\}$—where 1 denotes the commodity crop and 2 denotes the energy crop—for each unit of land allocated to the production of crop $i$. Before the farmer can produce energy crops, an additional fixed set up (site preparation) cost $s$ is incurred. Total output (supply) of crop $i$ is an increasing, twice-continuously differentiable, concave function of the allocated land, given by $Q_i = f_i(L_i) \equiv (\beta_i - \delta_i L_i)L_i$.[2] The supply of biomass is subject to a random, positive yield shock $\tilde{\epsilon}$ with cumulative distribution $G(\cdot)$, probability density function $g(\cdot)$, support $[\underline{\epsilon}, \overline{\epsilon}]$ $(0 \leq \underline{\epsilon} < \overline{\epsilon} < \infty)$ and finite mean. We assume random output takes a multiplicative form such that $Q_2(L_2, \tilde{\epsilon}) \equiv f_2(L_2)y(\tilde{\epsilon})$. We assume $y(\underline{\epsilon}) \geq 0$, $y'(\tilde{\epsilon}) > 0$; and $f_2(L_2)$ is independent of the yield distribution $G(\cdot)$. The expected spot price is $p$.

The biorefinery expects biofuel price $\alpha$ and faces a constant marginal processing cost $k$ for each unit of biofuel produced. He procures energy crops from the farmer at contract price $\omega$ and transforms the biomass into biofuel at the fixed input-output ratio $\gamma$. We refer the reader to Table 1 on page 16 for the complete list of notation.

### 3.3.2 Integrated Supply Chain

The vertically integrated supply chain again serves as our benchmark. The integrated channel allocates land toward energy crop production to maximize profit:

$$E[\Pi^I] \;=\; \max_{0 \leq L_2 \leq L} \quad E[\gamma(\alpha - k)f_2(L_2)y(\tilde{\epsilon}) - c_2 L_2 - s]$$

The unique optimal land use for energy crop production in the integrated system is:

$$L_2^I \;=\; \min\{L_I^\star\,,\, L\}$$

where $L_I^\star$ satisfies the first order condition:

$$f_2'(L_I^\star) = \frac{c_2}{\mu\gamma(\alpha - k)}$$

[2]We assume the farmer's land endowment is such that marginal output is always non-negative. In other words, $f_i'(L) \geq 0\ \forall i$.

### 3.3.3 Contracting with the Diversifying and Specializing Farmer

We evaluate a biorefinery's equilibrium pricing strategy under assumptions of a diversifying and specializing contractee (farmer). The model results obtained in Chapter 2 illustrate the pricing strategy when a participating farmer adds biomass feedstock to her crop mix. When a specializing farmer chooses to participate in energy crop production she maximizes expected profit from energy crop production alone. Any land not used in energy crop production will then be used to produce subordinate (commodity) crops.

Under the diversifying assumption, which we designate with the following accent on all variables exclusive to that scenario, $(\hat{\cdot})$, the biorefinery's pricing strategy determines the share of biomass in the farmer's crop mix. Therefore, the contract price tended to include a premium, where we define premium as the difference between the minimum contract price the farmer will accept and the biorefinery's equilibrium contract price. In the specializing assumption which we designate with the accent $(\check{\cdot})$, the biorefinery must offer a contract price which makes energy crop production (alone) at least as profitable as commodity crop production (i.e., a price greater or equal to the breakeven price).[3]

Our objective is to characterize the equilibrium contract price and resulting biomass allocation (supply) in each scenario. In so doing, we can quantify the effect of commodity market competition on the biorefinery's contract pricing strategy. Thus, again we limit our focus to the range of market conditions in which the diversifying farmer is constrained by her land resource and finds it optimal to make strictly positive allocations toward both commodity and energy crop production. Note, however, that in this specializing scenario competition is reflected implicitly via the farmer's reservation profit constraint.

[3]We assume the farmer will choose to specialize in energy crop production when expected profit from the two enterprises is equal.

## *3.4 Wholesale Contract*

Under the wholesale contract structure, the biorefinery offers to pay the farmer $\omega$ for each unit of biomass produced. If the farmer accepts the biorefinery's contract terms (i.e., her reservation profit condition is satisfied), she will allocate $L_2$ units of land toward energy crop production. The biorefinery chooses the wholesale price $\omega$ to maximize expected profit subject to gaining the farmer's participation. Let $E[\Pi_F^{NC}]$ denote the farmer's reservation profit level.

Under the specializing assumption, the biorefinery offers a contract price $\omega$ which solves the following bilevel optimization problem:

$$\hat{\mathcal{P}}_W \quad \max_{\omega} \quad E\left[\Big(\gamma(\alpha-k)-\omega\Big) f_2(\hat{L}_2(\omega))y(\tilde{\epsilon})\right]$$

$$\text{s.t.} \quad \begin{cases} \hat{L}_2(\omega) = \underset{L_2}{\operatorname{argmax}} \; E[\Pi_F^W(L_2)] & \text{(IC)} \\ E[\Pi_F^W(L_2)] \equiv E[\omega f_2(L_2)y(\tilde{\epsilon}) - c_2L_2 - s] \;\geq\; E[\Pi_F^{NC}] & \text{(IR)} \\ 0 \leq L_2 \leq L \end{cases} \tag{28}$$

While under the diversifying assumption the biorefinery chooses $\omega$ to solve:

$$\hat{\hat{\mathcal{P}}}_W \quad \max_{\omega} \quad E\left[\Big(\gamma(\alpha-k)-\omega\Big) f_2(\hat{\hat{L}}_2(\omega))y(\tilde{\epsilon})\right]$$

$$\text{s.t.} \quad \begin{cases} \hat{\hat{L}}_2(\omega) = \underset{L_2}{\operatorname{argmax}} \; E[\Pi_F^W(L_2)] & \text{(IC)} \\ E[\Pi_F^W(L_2)] \equiv & \\ \quad E[pf_1(L-L_2) + \omega f_2(L_2)y(\tilde{\epsilon}) - c_1(L-L_2) - c_2L_2 - s] \geq E[\Pi_F^{NC}] & \text{(IR)} \\ 0 \leq Ł_2 \leq L \end{cases} \tag{29}$$

The incentive compatibility (IC) constraints in $\hat{\mathcal{P}}_W$ and $\hat{\hat{\mathcal{P}}}_W$ (problems 28 and 29), require the farmer to choose the biomass allocation $L_2(\omega)$ that maximizes her expected profit. The individual rationality (IR) constraint ensures that contract terms allow the farmer to receive at least her reservation profit level (in expectation). In the previous chapter we proved the nonlinear IR constraint in $\hat{\hat{\mathcal{P}}}_W$ can be replaced by a linear, lower bound constraint on the contract price. Namely, $\omega \geq \omega_{min}$, where $\omega_{min}$ is the minimum wholesale price for which the farmer will accept the contract and allocate a positive quantity of land toward the production of energy crops. A similar substitution can be made in $\hat{\mathcal{P}}_W$. Let $\hat{\omega}_W$ and $\hat{\hat{\omega}}_W$ be the solutions to $\hat{\mathcal{P}}_W$ and $\hat{\hat{\mathcal{P}}}_W$, respectively.

**Proposition 7.** *When the farmer's IR constraint is not binding, the supply chain with a specializing farmer i) has a lower equilibrium contract price; ii) allocates more land toward energy crop production; and iii) achieves greater system profits relative to the supply chain with a diversifying farmer.*

*Proof. i)* $\hat{L}_2(\omega)$ and $\hat{\hat{L}}_2(\omega)$ denote the farmer's land allocation response function, for a given contract price $\omega$, in the specializing and diversifying supply chains, respectively. Solving the farmer's profit maximization problem we verify that her equilibrium allocation in each scenario satisfies:

$$\hat{\hat{\sigma}} = f_2'\left(\hat{\hat{L}}_2(\omega)\right)\frac{\partial \hat{\hat{L}}_2(\omega)}{\partial \omega}\frac{\omega}{f_2(\hat{\hat{L}}_2(\omega))} > f_2'(\hat{L}_2(\omega))\frac{\partial \hat{L}_2(\omega)}{\partial \omega}\frac{\omega}{f_2(\hat{L}_2(\omega))} = \hat{\sigma} \quad \forall \omega \quad (30)$$

Making use of Proposition 3 on page 24, in particular, $\omega^W = \dfrac{\gamma(\alpha - k)}{1 + {}^1\!/_\sigma}$, the inequality in (30) implies the biorefinery's (unconstrained) equilibrium wholesale price is higher in the diversifying chain than it is in the specializing chain since biomass supply is more elastic at every contract price $\omega$.

*ii)* To see that energy crop allocation is greater with a specializing farmer, we consider the farmer's first-order conditions (FOCs). The specializing farmer allocates land so that $f_2'(\hat{L}_2(\omega)) = \frac{c_2}{\mu\omega}$, while the diversifying farmer allocates land toward energy crop production in order to satisfy $f_2'(\hat{\hat{L}}_2(\omega)) = \frac{pf_1'(L - \hat{\hat{L}}_2(\omega)) - c_1 + c_2}{\mu\omega}$. Due to our tight land constraint, $pf_1'(L - \hat{\hat{L}}_2(\omega)) - c_1 > 0$; thus, $f_2'(\hat{L}_2(\omega)) < f_2'(\hat{\hat{L}}_2(\omega))$. Since $f_2(\cdot)$ is strictly increasing, $\hat{L}_2(\omega) > \hat{\hat{L}}_2(\omega)$ for any $\omega > 0$. Therefore, for any contract offering at least the maximum of the two minimum acceptable wholesale prices (namely, for $\omega \geq \max\{\hat{\omega}_{min}, \hat{\hat{\omega}}_{min}\}$),[4] the specializing farmer will allocate more land than the diversifying farmer.

We have shown that for a given contract price, the specializing farmer allocates more land toward energy crop production than the diversifying farmer. However, we have not shown that energy crop allocation, evaluated at the equilibrium contract price, is greater in the specializing supply chain.

Suppose not. Denote the equilibrium solutions for the specializing and diversifying farmers, respectively, as $\{\hat{\omega}, \hat{L}_2(\hat{\omega})\}$ and $\{\hat{\hat{\omega}}, \hat{\hat{L}}_2(\hat{\hat{\omega}})\}$. If $\hat{L}_2(\hat{\omega}) < \hat{\hat{L}}_2(\hat{\hat{\omega}})$, then by the discussion above, the biorefinery could induce the allocation $\hat{\hat{L}}_2(\hat{\hat{\omega}})$ from the specializing farmer at a contract price $\hat{\omega} + \Delta < \hat{\hat{\omega}}$ and strictly increase his profit. Therefore, since the biorefinery prefers $\{\hat{\omega}, \hat{L}_2(\hat{\omega})\}$ to $\{\hat{\omega} + \Delta, \hat{\hat{L}}_2(\hat{\hat{\omega}})\}$ in the specializing supply chain it must be that $\hat{L}_2(\hat{\omega}) > \hat{\hat{L}}_2(\hat{\hat{\omega}})$.

*iii)* To see that decentralized supply chain profit is greater with a specializing farmer we evaluate the following inequality, where $\mu \equiv E[y(\tilde{\epsilon})]$

$$\mu\gamma(\alpha - k)f_2(\hat{L}_2(\hat{\omega})) - c_2\hat{L}_2(\hat{\omega}) - s > \mu\gamma(\alpha - k)f_2(\hat{\hat{L}}_2(\hat{\hat{\omega}})) - c_2\hat{\hat{L}}_2(\hat{\hat{\omega}}) - s \tag{31}$$

Rearranging we obtain

$$\frac{f_2(\hat{L}_2(\hat{\omega})) - f_2(\hat{\hat{L}}_2(\hat{\hat{\omega}}))}{\hat{L}_2(\hat{\omega}) - \hat{\hat{L}}_2(\hat{\hat{\omega}})} > \frac{c_2}{\mu\gamma(\alpha - k)} \tag{32}$$

FOCs from the integrated channel require $f_2'(L_2^I) = \frac{c_2}{\mu\gamma(\alpha-k)}$. Again, since $f_2(\cdot)$ is strictly increasing on $[0, L]$ the inequality in (31) is confirmed by (32) which implies the decentralized system allocation is lower than that in the integrated channel. □

It is not intuitive that a farmer who chooses to specialize in energy crop production should receive a lower contract price than a farmer who prefers to dedicate only a

[4]Where, as before, $\omega_{min}$ denotes the minimum acceptable contract price, and $\hat{x}$ and $\hat{\hat{x}}$ signifies that the parameter in question belongs, respectively, to the specializing and diversifying farmer.

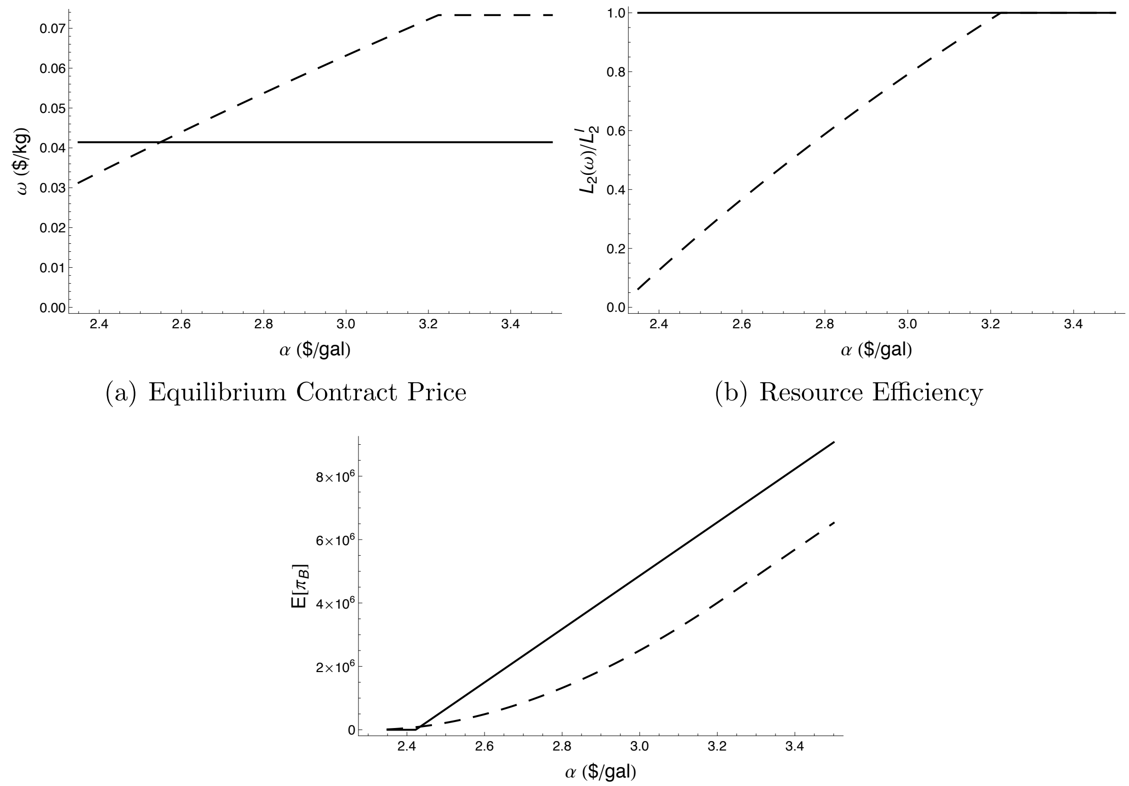
portion of her crop mix to biomass feedstock. We note, however, that the specializing farmer requires a higher price for participation than the diversifying farmer does.

### 3.4.1 Sensitivity Under Wholesale Contract

The result in Proposition 7 does not provide any insight into the relative performance of each supply chain when either or both of the systems are constrained by the farmer's reservation profit requirement. Using a numerical example we compare performance as key parameters vary: $\alpha$, the expected biofuel price; $\delta_2$, the marginal yield reduction rate; $p$, the expected spot price; and, $L$ the farmer's fixed land resource. The farmer's reservation profit is set as the maximum profit achievable under commodity production alone, given her available land resource. In other words, given $p$, $\beta_1$, $\delta_1$, and $c_1$, reservation profit $E[\Pi_F^{NC}] = pf_1(L_1^{NC}) - c_1 L_1^{NC}$. Where $L_1^{NC}$ denotes the optimal land use before any contract is offered. Under benchmark conditions we designate $L \equiv L_1^{NC}$. We calibrate our sensitivity study using the benchmark parameter values from Chapter 2. The table has been reproduced here for easy reference.

Table 4: Benchmark Parameter Values

| Parameter | Benchmark Value | | Description | Sensitivity Range |
|---|---|---|---|---|
| $\beta_1$ | 8,655 | $kg/ha$ | Max commodity yield per area | |
| $\beta_2$ | 10,000 | $kg/ha$ | Max energy crop yield per area | |
| $\delta_1$ | 0.1 | $kg/ha^2$ | Marginal yield reduction rate (commodity) | |
| $\delta_2$ | 0.05 | $kg/ha^2$ | Marginal yield reduction rate (energy crop) | [ 0.001, 0.3 ] |
| $p$ | 0.14 | $\$/kg$ | Commodity price | [ 0.11, 0.19 ] |
| $c_1$ | 917 | $\$/ha$ | Commodity production cost | |
| $c_2$ | 230 | $\$/ha$ | Energy crop production cost | |
| $L$ | 10,525 | $ha$ | Total available land resource | [ 9,000, 19,442 ] |
| $s$ | 690 | \$ | Fixed set up cost (energy crop) | |
| $\mu$ | 80 | % | Expected harvestable output | |
| $\gamma^{-1}$ | 9.47 | $kg/gal$ | Input-output ratio (energy crop to biofuel) | |
| $\alpha$ | 2.7 | $\$/gal$ | Expected biofuel price | [ 2.35, 3.50 ] |
| $k$ | 2.03 | $\$/gal$ | Marginal biofuel production cost | |




(a) Equilibrium Contract Price

(b) Resource Efficiency

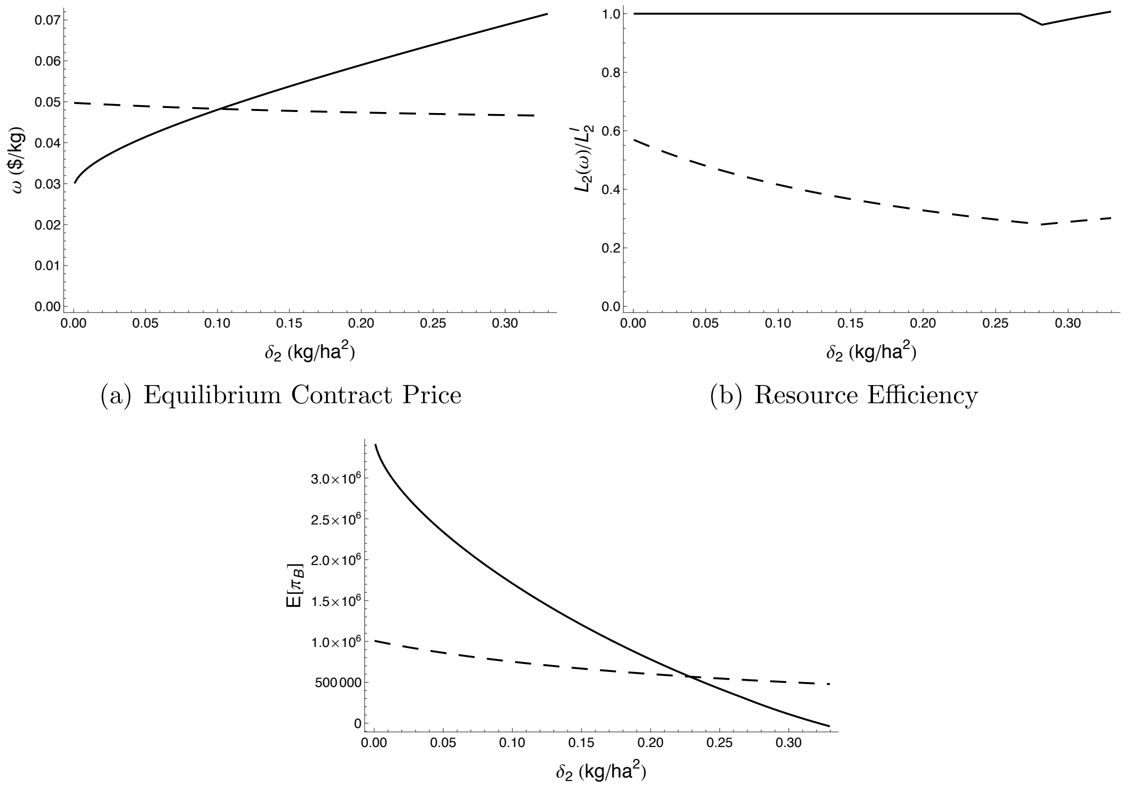
(c) Biorefinery Profit

Figure 8: Effect of biofuel price $\alpha$ on pricing strategies, equilibrium energy crop allocations and biorefinery profit under contract with the specializing farmer (solid line) and diversifying farmer (dashed line). Resource efficiency, $L_2(\omega)/L_2^I$, denotes the ratio of decentralized energy crop allocation to vertically integrated energy crop allocation.

Figure 8 illustrates the difference in pricing strategy and energy crop allocation for specializing and diversifying farmers at various expected biofuel prices, $\alpha$. The specializing farmer has a higher minimum acceptable contract price; however, at that breakeven price it is optimal for her to use her entire land resource in energy crop production. At low expected biofuel prices the breakeven price is constraining for the biorefinery. But, at every expected biofuel price we obtain the result familiar to buyer-driven channels: the biorefinery extracts all system profit above the farmer's reservation level. This is illustrated by the equilibrium contract price curve in the specializing supply chain which is flat, see Figure 8(a). In contrast, when contracting with the diversifying farmer the biorefinery must offer a premium over the farmer's minimum acceptable price in order to secure a greater supply of feedstock and take advantage of profit in the biofuel market. But, as illustrated in Figure 8(b), only a sufficiently optimistic biofuel outlook (high $\alpha$) encourages the biorefinery to offer the premium required to induce an energy crop allocation comparable to that of the specializing farmer.

Resource efficiency, ${}^{L_2(\omega)}/_{L_2^I}$, denotes the ratio of energy crop allocation in the specialized– and diversified (decentralized) supply chains to that in the vertically integrated channel, Figure 8(b). For the range of biofuel prices considered, the integrated channel is severely constrained by the fixed land resource available for switchgrass production. As such, there are conditions under which the decentralized systems can attain integrated system performance levels. This occurs at a much lower contract price in the specialized supply chain as compared with the diversified channel. In Section 3.4.2 we relax the land constraint to evaluate performance relative to the integrated system, but from the figure it is clear that even at substantial premiums over the breakeven price, energy crop allocation by a diversifying farmer is significantly lower than that of the specializing farmer. Note, however, that at low biofuel prices, when the specializing farmer's reservation profit is an unaffordable binding constraint, the profit maximizing biorefinery would prefer to contract with a diversifying farmer to earn a small, but positive profit, Figure 8(c).

Figure 9 illustrates pricing strategies and energy crop allocations under varying marginal yield reduction rates $\delta_2$. Recall, the marginal yield reduction rate reflects diminishing returns in crop production due to heterogeneous land quality—alternatively, risk aversion, etc. The minimum acceptable contract price is increasing in $\delta_2$ for both types of farmers, however, its effect on equilibrium pricing differs, see Figure 9(a). The farmer's minimum required contract price is not a binding constraint with the diversifying farmer, but the specializing farmer's required price binds at modest levels of the variable ($\delta_2 > 0.07$). Ceteris paribus, higher $\delta_2$ makes energy




(a) Equilibrium Contract Price

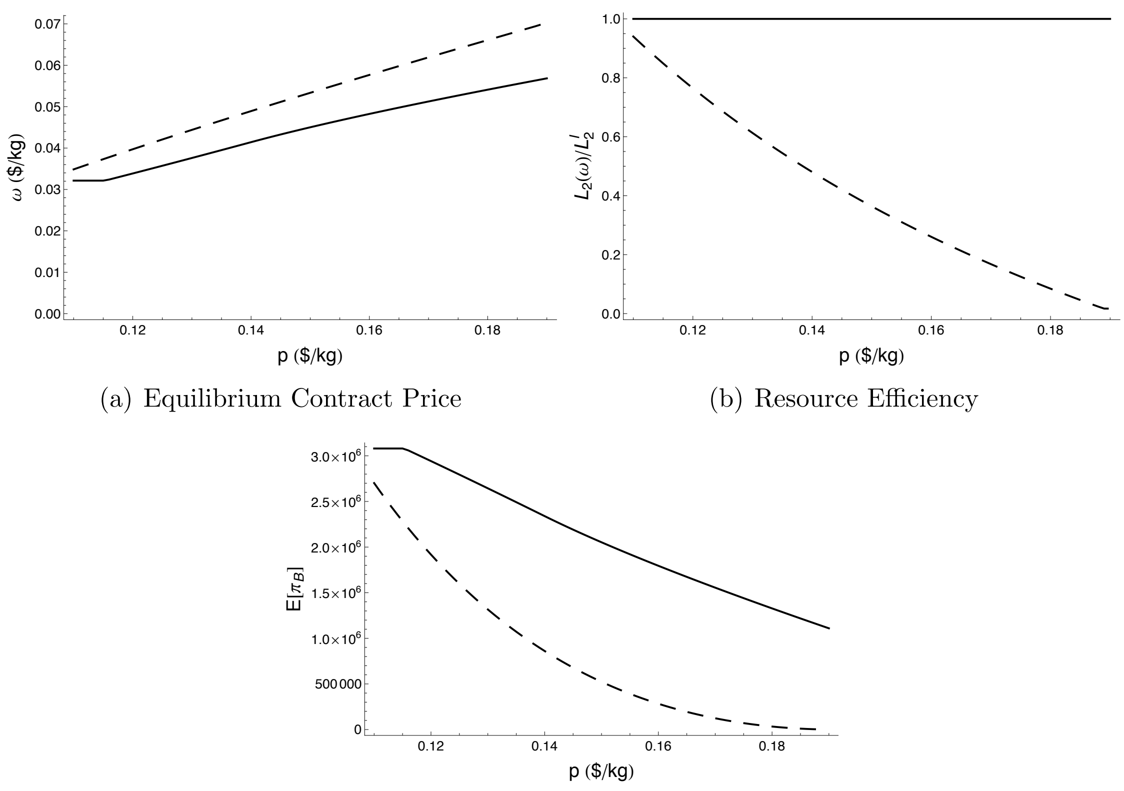
(b) Resource Efficiency

(c) Biorefinery Profit

Figure 9: Effect of marginal yield reduction rate $\delta_2$ on pricing strategies, equilibrium energy crop allocations and biorefinery profit under contract with the specializing farmer (solid line) and diversifying farmer (dashed line). Resource efficiency, $L_2(\omega)/L_2^I$, denotes the ratio of decentralized energy crop allocation to vertically integrated energy crop allocation.

crop production less favorable, as compared with commodity crop production. However, if the specializing farmer is to adopt energy crops it has to be profitable enough to replace commodity production, thus commanding a substantial unit price. For the diversifying farmer, energy crop production just has to be profitable enough to enter the crop mix, as opposed to replacing the current crop mix, so that the equilibrium price is significantly lower yet it still offers a premium over the farmer's minimum requirement.

At her breakeven price, the specializing farmer finds it optimal to plant most of her land to energy crops so that resource efficiency is substantially greater than in the diversifying supply chain, Figure 9(b). As a result, despite earning a lower profit margin on each unit of biomass, the biorefinery still earns more profit with the specializing farmer (at low and moderated levels of $\delta_2$) due to a greater volume of biofuel sales, Figure 9(c). On the other hand, at high levels of $\delta_2$, the specializing farmer's minimum required price is binding and leaves little profit margin on each unit of biomass, but average yields are also substantially lower (due to diminishing returns) so that the biorefinery cannot make up profit via biofuel sales. Therefore, when biomass productivity is low ($\delta_2$ is high) the biorefinery would prefer to contract with a diversifying farmer since he could pay a lower unit price and increase his margin on each unit of biofuel produced.




(a) Equilibrium Contract Price

(b) Resource Efficiency

(c) Biorefinery Profit

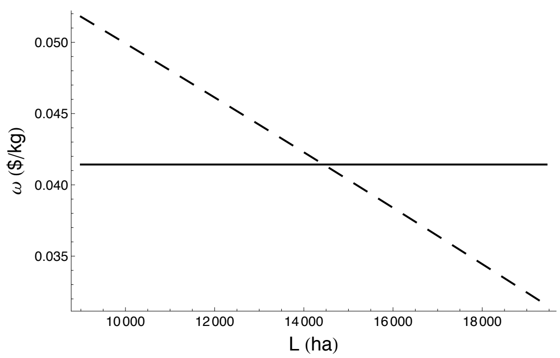
Figure 10: Effect of commodity price $p$ on pricing strategies, equilibrium energy crop allocations and biorefinery profit under contract with the specializing farmer (solid line) and diversifying farmer (dashed line). Resource efficiency, ${L_2(\omega)}/{L_2^I}$, denotes the ratio of decentralized energy crop allocation to vertically integrated energy crop allocation.

A high expected commodity price makes feedstock acquisition from both types of farmers more costly, Figure 10(a). When $p >$\$0.145/kg the specializing farmer's minimum required price constrains biorefinery profit. The diversifying farmer's required contract price only constrains the biorefinery at expected commodity prices greater than \$0.189/kg. Proposition 7 proved that, when neither farmer's reservation profit constrains the biorefinery (\$0.11/kg$\leq p \leq$\$0.145/kg in the Figure), the diversifying farmer commands a higher contract price. However, as illustrated in Figure 10(a), the diversifying farmer wins a higher price even when the specializing farmer's reservation constraint is binding, and when she would otherwise have land left fallow (not planted to commodities) in the absence of a biomass contract.[5] This suggests the importance of explicit competition and the benefit (additional market power) it confers on the diversifying farmer via contract premiums (over that of reservation profit alone since both farmers have the same reservation).

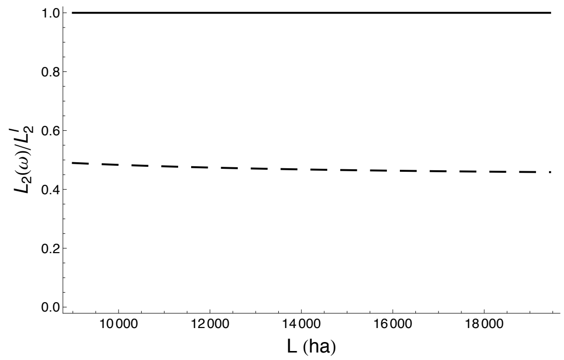
The specializing farmer earns a premium in the region where her contract price is flat. In that region her minimum required price is not sufficient to induce full use of her land for energy crop production, but the biorefinery finds it optimal to offer the premium required to induce full utilization. In contrast, despite higher premiums, the diversifying farmer does not completely abandon commodity production in this sensitivity range, see Figure 10(b). At high expected commodity prices, competition for a share of the crop mix is much more costly for the biorefinery than the specializing farmer's binding reservation profit which is evident from his expected profit, see Figure 10(c).

For farmers with a large land holding, competing with commodity production (at its benchmark value) is not costly for the biorefinery. For smaller land holdings ($L < 10,525$ ha) the diversifying farmer requires a substantial premium to allocate

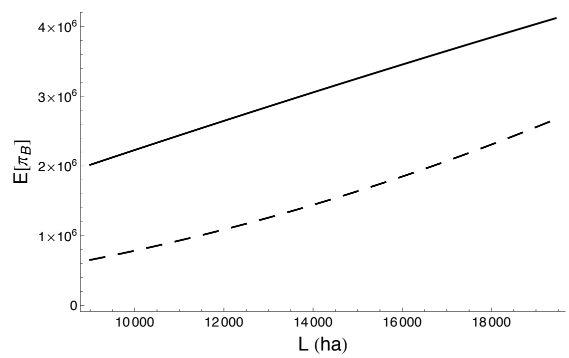
[5] Recall that for this numerical example we set the farmer's total land resource equal to her optimal commodity crop allocation under benchmark parameter values ($L_1^{NC}$).




(a) Equilibrium Contract Price




(b) Resource Efficiency




(c) Biorefinery Profit

Figure 11: Effect of total land availability $L$ on pricing strategies, equilibrium energy crop allocations and biorefinery profit under contract with the specializing farmer (solid line) and diversifying farmer (dashed line). Resource efficiency, ${}^{L_2(\omega)}/_{L_2^I}$, denotes the ratio of decentralized energy crop allocation to vertically integrated energy crop allocation.

any meaningful amount of land toward energy crop production since her land resource is not sufficient for desired commodity production alone, see Figures 11(a) and 11(b). At large land holdings ($L > 10,525$ ha) the diversifying farmer would leave land fallow at the expected spot price, so that the biorefinery can secure feedstock at lower prices. The specializing farmer's minimum required price is not binding for the biorefinery; and, at that price she is willing to use all of her land for energy crop production.

When land is tight, the biorefinery's biofuel price outlook discourages competition with commodity crop production for the farmer's land when contracting with a diversifying farmer. Competition is costly since the premiums required to compete with commodity production result in lower profit margins on the biomass procured.

For farmers with larger land holdings, competing with commodity production for space in the crop mix is less costly. However, the less costly is competition, the less the biorefinery competes. The biorefinery offers diversifying farmers with larger land holdings a lower premium than diversifying farmers with smaller holdings, see Figure 11(a). The biorefinery takes advantage of the fact that commodity production is not profitable on all of the farmer's hectares. So rather than offer a higher contract price to secure greater biomass production, the biorefinery prefers to reduce the contract price and extract greater profits from the system indicating the biorefinery's profit motives (double marginalization) drive system inefficiency, not commodity market competition, Figure 11(b).

In each of these sensitivity studies system performance with a specializing farmer is better than performance with a diversifying farmer. Nevertheless, there are circumstances in which a profit maximizing biorefinery prefers the lower required contract prices of a diversifying farmer. However, in each of these studies the vertically integrated channel was constrained by the land resource over the majority of parameter ranges considered (the exception being $\delta_2 \geq 0.28$ in Figure 9). To evaluate performance in each decentralized supply chain relative to performance of the vertically integrated channel, we relax the land constraint so it no longer binds the vertically integrated channel. The farmer's reservation profit level does not alter her energy crop allocation, it only dictates whether she will accept a contract or not. Therefore, inefficiency in the system with a specializing farmer provides an estimate of double marginalization—the extent to which profit motives prohibit the system optimal supply of biomass (biofuel). While inefficiency in the diversifying supply chain provides an estimate for inefficiency due to the combined effects of double marginalization and commodity market competition. We use resource efficiency (as opposed to system efficiency as is common in the supply chain literature) to estimate effects since large discrepancies in resource use, the variable of interest, do not necessarily reflect large discrepancies in supply chain profits due to diminishing returns (the marginal yield reduction rate).

### 3.4.2 Inefficiency Under Wholesale Contract

We relax the land constraint so that it is no longer binding in the vertically integrated channel and estimate the relative importance of profit and competition at various parameter values. Table 5 illustrates the relationship between contract efficiency and the expected biofuel price $\alpha$, marginal yield reduction rate $\delta_2$, and the expected spot price $p$. In the supply chain with a specializing farmer there is no explicit competition from commodity production, therefore any inefficiency is due to double marginalization (DM). In the supply chain with a diversifying farmer inefficiency is due to the combined effect of double marginalization and explicit competition for scarce land. Unless otherwise specified, all parameters are at their benchmark levels except $L$. Now we set $L$ equal to the integrated channel's unconstrained optimal energy crop allocation at the given specified parameter values. Naturally, when the integrated channel desires large amounts of land to maximize biofuel production there will be little competition between commodity and energy crops. As a proxy for competition in those instances we maintain the requirement that energy crop production be as profitable for the farmer as commodity production.

In general, the double marginalization effect—the *inefficiency* resulting from DM—is low at higher expected biofuel prices, higher marginal yield reduction rates and higher expected commodity prices. Whereas the combined effect—*inefficiency* due to both DM and commodity market competition—is low at higher biofuel prices, higher marginal yield reduction rates but lower commodity prices. At higher biofuel prices, the biorefinery is willing and able to offer higher contract prices in order to induce a greater allocation thereby reducing the double marginalization effect. Higher prices make competition affordable, thus reducing the combined effect. The apparent

Table 5: Double Marginalization (DM) vs Combined Effect: Inefficiency in the Supply Chain with Specializing and Diversifying Farmers Under Wholesale Contract

| | | DM | Combined |
|---|---|---|---|
| $\alpha$ | 2.55 | 35.8% | 87.7% |
| | 2.75 | 42.8% | 84.1% |
| | 3.15 | 39.1% | 78.1% |
| $\delta_2$ | 0.05 | 43.4% | 85.0% |
| | 0.15 | 21.6% | 70.3% |
| | 0.25 | 7.3% | 63.2% |
| $p$ | 0.12 | 43.4% | 83.2% |
| | 0.14 | 43.4% | 85.0% |
| | 0.16 | 29.8% | 86.4% |

increase in double marginalization from $\alpha = \$2.55$/gal to $\alpha = \$2.75$/gal, is due to a binding IR constraint. When the expected biofuel price is low, the biorefinery prefers to offer a lower wholesale price, but must satisfy the farmer's participation constraint. At higher expected biofuel prices the biorefinery is free to offer the wholesale price which maximizes his profit, thus the increase in DM from a biofuel price at which the supplier's minimum required wholesale price is a binding constraint to a biofuel price at which it does not bind.

At high yield reduction rates DM is low as both land use in the integrated channel is relatively low and the farmer's minimum required wholesale price is high. Although yields are declining, the minimum required wholesale price is sufficient to warrant substantial land use by the specializing farmer. The combined effect is lower primarily due to the reduction in double marginalization; the competition effect, however, is quite substantial even as double marginalization is nearly eliminated at very high yield reduction rates (e.g. $\delta_2 = 0.25$).

At high expected spot prices the farmer's reservation profit is high and the biorefinery must sacrifice its own profit to gain contract acceptance, thus low DM at high expected commodity prices. However, in the supply chain with a diversifying farmer, a high spot price increases both the supplier's reservation profit and direct competitive effects. That the combined effect is high despite low DM suggests that competition has a bigger effect on system performance than profit motives.

Perakis and Roels [88] find that inefficiency due to double marginalization in a two-stage decentralized supply chain operating under price-only (wholesale) contract is at least 42%. Though their modeling assumptions are very different from ours, including a zero reservation profit assumption, most of our DM estimates are similar. Interestingly, they find that when there are multiple, identical retailers (buyers), each of which proposes a wholesale contract to a single supplier, competition between the retailers increases the inefficiency due to double marginalization. In our case, in which there is indirect competition between a contract proposing retailer (biorefinery) and a distinct, exogenous spot market, competition decreases the inefficiency due to double marginalization.

What is especially interesting about the results in Table 5 is the magnitude of difference between the DM and combined effects. It is clear that even when competing against a commodity market with thin margins feedstock acquisition will be a challenge. And while marginal (less productive) land is attractive since commodity competition is virtually eliminated, low biomass yields on marginal land may make acquisition as costly, albeit without the potentially adverse impact on the food system.

## *3.5 Capacity Procurement Contract*

Under the capacity procurement contract the biorefinery pays per unit area—for each of the $L_2$ units dedicated toward energy crop production—as opposed to per unit biomass actually produced. If the farmer accepts the biorefinery's contract terms she will dedicate the agreed upon $L_2$ units of land toward energy crop production. The biorefinery chooses the capacity procurement price $\omega$ to maximize his expected profit subject to the farmer accepting the contract.

In the supply chain with a specializing farmer, the biorefinery solves the following bilevel optimization problem:

$$\hat{\mathcal{P}}_{CP} \quad \max_{\omega} \quad E\left[\gamma(\alpha-k)f_2\left(\hat{L}_2(\omega)\right)y(\tilde{\epsilon}) \;-\; \omega\hat{L}_2(\omega)\right]$$
$$\text{s.t.} \quad \begin{cases} \hat{L}_2(\omega) = \dfrac{E[\Pi_F^{NC}]+s}{\omega-c_2} & \text{(IR)} \\ 0 \leq L_2 \leq L \end{cases} \tag{33}$$

While in the supply chain with a diversifying farmer he solves:

$$\hat{\hat{\mathcal{P}}}_{CP} \quad \max_{\omega} \quad E\left[\gamma(\alpha-k)f_2\left(\hat{\hat{L}}_2(\omega)\right)y(\tilde{\epsilon}) \;-\; \omega\hat{\hat{L}}_2(\omega)\right]$$
$$\text{s.t.} \quad \begin{cases} \hat{\hat{L}}_2(\omega) = \underset{L_2}{\operatorname{argmax}} \;\; E[\Pi_F^{CP}(L_2)] & \text{(IC)} \\ E[\Pi_F^{CP}(L_2)] \equiv & \\ \qquad pf_1(L-L_2)+(\omega-c_2)L_2-c_1(L-L_2)-s \;\geq\; E[\Pi_F^{NC}] & \text{(IR)} \\ 0 \leq L_2 \leq L \end{cases} \tag{34}$$

In the specializing supply chain, the biorefinery can always extract all system profit above the farmer's reservation level with a capacity procurement contract. Since the farmer is assumed to accept any contract that provides her minimum requirement, the capacity procurement price must satisfy $(\omega-c_2)L_2 - s \geq E[\Pi_F^{NC}]$ (see the IR constraint in problem 33). As a result, the biorefinery's pricing decision is a nonlinear function of the farmer's land resource, taking the form of a quantity discount pricing scheme. For greater land allocation, the biorefinery can offer a lower per unit (area) price as total procurement will be sufficient to satisfy the farmer's IR constraint. However, if fewer hectares are desired, the per unit (area) price must be higher in order to satisfy the minimum profit requirement.[6]

[6] Tomlin [106] also demonstrates that in a supply chain in which both the supplier and biorefinery

**Proposition 8.** *When contracting with a specializing farmer it is always optimal to induce the integrated system's energy crop allocation, $L_2^I$.*

*Proof.* Let $\omega(\hat{L}_2)$ denote the inverse land allocation function: it is the minimum contract price the biorefinery can offer for $L_2$ units of land that will be accepted by the specializing farmer, $\omega(\hat{L}_2) = \frac{E[\Pi_F^{NC}]+s+c_2\hat{L}_2}{\hat{L}_2}$. Then, the biorefinery's objective is to choose the land allocation $\hat{L}_2$ that maximizes his expected profit. $\hat{\mathcal{P}}_{CP}$ can be rewritten as:

$$E[\Pi_B] = \max_{0\leq L_2\leq L} \quad \mu\gamma(\alpha-k)f_2(\hat{L}_2) - \omega(\hat{L}_2)\hat{L}_2 \tag{35}$$

It is easy to verify that second-order sufficient conditions for concavity of the biorefinery's expected profit function are satisfied. The biorefinery's objective function is well behaved and first–order conditions are necessary and sufficient in determining the optimal capacity level.

$$\mu\gamma(\alpha-k)f_2'(\hat{L}_2) - \left[\omega(\hat{L}_2) + \hat{L}_2\cdot\omega'(\hat{L}_2)\right] = 0 \tag{36}$$

The biorefinery's first-order condition, equation (36), reduces to $f_2'(\hat{L}_2) = \frac{c_2}{\mu\gamma(\alpha-k)}$, the same condition which characterizes the integrated channel's equilibrium allocation. □

In the supply chain with diversifying farmer, $\omega(\hat{\hat{L}}_2) = pf_1'(L-\hat{\hat{L}}_2) - c_1 + c_2$. Given commodity market conditions, the capacity procurement price is a linear function of the desired land allocation. In the previous chapter we showed that under certain conditions, the integrated system's allocation is feasible (both the farmer and biorefinery earn positive profits); however, it is not an equilibrium outcome. The result indicates a degree of flexibility offered by the capacity procurement contract that is not admitted by the wholesale contract. When the biofuel price is sufficiently high, the biorefinery can achieve the integrated system's performance without sacrificing

must build capacity, there exist quantity discount contracts that can coordinate the supply chain which leave the supplier with her reservation profit.

too much profit. But because the biorefinery can extract all system profits above the farmer's reservation level when contracting with a specializing farmer, the biorefinery is guaranteed system optimal performance without having to sacrifice any profit.

### 3.5.1 Capacity Procurement Efficiency

As shown in Proposition 8 there is no double marginalization effect in the supply chain with a specializing farmer under capacity procurement contract. Because the biorefinery, who acts as Stackelberg leader, absorbs the diminishing returns to biomass production, the interaction between the farmer and biorefinery is reduced to a scenario similar to the full information, forced compliance scenarios in [22] and [46]. Though no inefficiency is present in the specializing farmer chain, we compare equilibrium contract prices in both decentralized supply chains and evaluate efficiency in the supply chain with diversifying farmer at varying parameter values. As before, the notation $\hat{x}$ and $\hat{\hat{x}}$ signifies the parameter in question belongs, respectively, to the specializing and diversifying farmer.

Table 6 presents the equilibrium capacity procurement price in the supply chain with specializing farmer ($\hat{\omega}$), the diversifying farmer's minimum acceptable procurement price ($\hat{\hat{\omega}}_{min}$), the equilibrium procurement price for the diversifying farmer ($\hat{\hat{\omega}}$), and resource efficiency in the supply chain with diversifying farmer ($\hat{\hat{L}}_2(\hat{\hat{\omega}})/L_2^I$). The bold row depicts performance under benchmark conditions.

As with the wholesale contract, at higher expected biofuel prices $\alpha$, the resource efficiency of a capacity procurement contract with diversifying farmer is higher. The equilibrium contract price for the specializing farmer is constant in $\alpha$ since the system is constrained by the farmer's available land ($\hat{L}_2 = L_2^I = L$). The price for the diversifying farmer is increasing in $\alpha$, reflecting the biorefinery's willingness and ability to compete with commodity production.

At high yield reduction rates $\delta_2$, the diversifying farmer's equilibrium procurement

Table 6: Performance Under Capacity Procurement Contract with a Specializing and Diversifying Farmer

| | | $\hat{\omega}$ | $\hat{\hat{\omega}}_{min}$ | $\hat{\hat{\omega}}$ | $\hat{\hat{L}}_2(\hat{\omega})/L_2^I$ |
|---|---|---|---|---|---|
| $\alpha$ | 2.55 | 377.42 | 236.22 | 327.03 | 32.92% |
| | 2.75 | 377.42 | 236.22 | 400.59 | 57.89% |
| | 3.15 | 377.42 | 236.22 | 524.70 | 100% |
| $\delta_2$ | 0.01 | 377.42 | 236.22 | 394.67 | 55.88% |
| | 0.03 | 377.42 | 236.22 | 388.39 | 53.75% |
| | 0.15 | 377.42 | 236.22 | 358.91 | 43.74% |
| | 0.3 | 386.82 | 236.22 | 334.58 | 37.75% |
| $p$ | 0.12 | 259.33 | 230.13 | 307.87 | 82.69% |
| | **0.14** | **377.42** | **236.22** | **382.58** | **51.77%** |
| | 0.16 | 529.46 | 367.65 | 455.17 | 27.96% |
| $L$ | 9,000 | 398.77 | 278.92 | 405.89 | 52.85% |
| | 15,000 | 333.44 | 230.15 | 314.18 | 49.88% |
| | 20,000 | 307.57 | 230.07 | 237.75 | 48.76% |

price is lower, as is resource efficiency. At high yield reduction rates average yields are low; therefore, the biorefinery desires less capacity—this is best exemplified by $\delta_2 = 0.3$ in the table, at which point the farmer's land availability does not constrain the system. But in order to satisfy the specializing farmer's participation requirement it must offer a higher capacity procurement price. Since the farmer is immune to any production risks under capacity procurement contract, the only way to secure a greater share of the diversifying farmer's crop mix (for low $\delta_2$) is through higher contract prices.

When the expected spot price $p$ is high the specializing farmer's reservation profit (and thus minimum required procurement price) is high. The reservation profit and commodity crop competition in the diversifying farmer supply chain are higher at higher expected spot prices as well. However, since the specializing farmer requires energy crop production alone to be as profitable as commodity crop production, the specializing farmer requires a substantially larger capacity procurement price to produce biomass when commodities are especially profitable ($p = 0.16$ in the Table 6).

The competition for land wins the diversifying farmer a substantial premium. When the available land resource is constraining, even in the absence of energy crop production (e.g. $L = 9,000$ in Table 6), the diversifying farmer requires a substantial premium in order to participate at the biorefinery's desired level. Recall from the previous chapter that under capacity procurement contract the farmer's commodity allocation is independent of $L$. So offering a high procurement price is the only way to secure a substantial supply of biomass. In contrast, a quantity discount structure emerges in the specializing supply chain, as is readily apparent from the relationship between $\hat{\omega}$ and $L$ in the table. At greater land holdings (e.g. $L = 20,000$) however, the biorefinery can secure land from the diversifying farmer if she is offered a capacity procurement price that is a small markup above the total cost of production since the land would otherwise be left fallow.

## 3.6 Conclusions

In this chapter we compare the design of two contract structures, wholesale (price-only) and capacity procurement, for two types of contract adopting farmers, the diversifying farmer who adds a contracted crop to her crop mix and a specializing farmer who will make the contracted crop her dominant output. There is much to be learned about contracting in agriculture; not least of these, the reasons producers and buyers choose to enter into contracts. Many producers cite reduced price/income and yield risks as a reason for contracting. Farmers who are particularly risk averse may sacrifice income in order to reduce or eliminate their exposure to risk. But as noted in [75], contracts are not the only income risk reducing tools (e.g., hedging, insurance) and risk reduction does not explain the premiums earned by some farmers over average marketing year spot prices for the same commodity. Our analysis shows that the reasons a farmer chooses to produce under contract, and hence the type of farmer she would be, greatly influences the contract terms a biorefinery would use to secure his desired feedstock production and the resulting profitability (viability) of a biofuel industry. The specializing farmer we have considered would tend to be very sensitive to price fluctuations and prefer the guaranteed prices associated with contract production to the uncertainty of spot market production. Whereas the diversifying farmer might be interested in producing a differentiated crop for which transaction costs in the spot market are too high, or contracting as part of an overall risk reducing strategy.

An important source of risk that is integral to this particular problem is the yield uncertainty with respect to energy crop production. Under the capacity procurement contract structure this risk does not effect the farmer, however, under the wholesale structure it would be an important determinant of a farmer's willingness to accept a contract. Since this particular risk we are interested in is so idiosyncratic, attempting to characterize it by anything other than some expected belief about its value would be unjustifiable. However, as the research on best management practices as well as site and variety specific average yields continues to be published and disseminated, this particular risk will be reduced.

Using biomass contracts for biofuel production as an application, we find that when designing a wholesale contract for a specializing farmer, the equilibrium wholesale price tends to be lower than what would be offered a diversifying farmer, yet a greater land allocation can be expected. Similarly, we find that when offering a capacity procurement contract to a specializing farmer, a quantity discount price structure emerges and supply chain coordination is expected.

In order to understand the impact of competition from the commodity market on contract terms and supply chain performance, we relaxed the land constraint for the integrated channel and estimated the double marginalization and combined effects—inefficiency in the specializing– and diversifying supplier chains, respectively. Inefficiency results for the wholesale and capacity procurement contract structures are quite different. Under wholesale contract, the marginal yield reduction rate directly effects the farmer. Consequently, the relative profit and production efficiency of commodity crops plays a significant role in the diversifying farmer's energy crop allocation decision, even when the biorefinery is willing to pay a premium for biomass. In contrast, the capacity procurement contract transfers production risk to the biorefinery since he pays per unit land as opposed to per unit biomass under this contract structure. As a result, the commodity market has little effect on system performance when land is available in abundance, and inefficiency arises primarily from the biorefinery's profit motive.

In the supply chain literature, an agent's alternatives are typically reflected in their reservation profit. However, in a context like agriculture in which production diseconomies exist (due to varying soil quality, increased risks of pests, etc.) and there tends to be a preference for diversification in production, it will be important to design contracts with explicit account of these characteristics, especially since agricultural land is fixed in all but possibly the long-term. Considering reservation profit alone (breakeven pricing) is not likely to be useful in securing biomass feedstock in the near term; and as illustrated by the diversifying farmer, competing for space in a farmer's crop mix can be quite costly. In the context of a nascent industry like next-generation biofuels where supplier participation is essential to market success but alternative production options for the supplier abound, the results obtained in this study highlight the important tradeoff between earning profit and securing feedstock.

# CHAPTER IV

# BIOMASS FEEDSTOCK CONTRACTS: ROLE OF LAND QUALITY AND YIELD VARIABILITY IN NEAR TERM FEASIBILITY

## *4.1 Introduction*

In recent years there have been many studies which estimate potential biomass feedstock availability in the United States and the resultant impacts on agriculture and the environment. Several models in particular, FAPRI, FASOM, GTAP, and POLYSYS, have been used extensively to evaluate the impacts of bioenergy policy on the agricultural and energy sectors, as well as the national economy. These partial and general equilibrium models evaluate deviations from baseline projections of the agricultural sector, over several decades, as the system adjusts to meet various policy goals or responds to various system shocks.

These models are useful in evaluating potential long-term, cross-sectoral effects of policy. However, these models are only as good as their baseline projections and their assumptions about the state of the world over the course of multiple decades. In this chapter we extend the modeling framework developed in Chapter 2 to estimate potential feedstock availability and cropland conversion over a five year period, with particular emphasis on the importance of payment structure, feedstock yield variability, and commercial scalability of feedstock production.

As a case study, we apply our model to switchgrass production in Tennessee. Switchgrass is a bioenergy feedstock native to North America; it was deemed a model bioenergy crop by the Biofuels Feedstock Development Program (BFDP) [80, 27]. Due to higher switchgrass yields and lower land rents (relative to yield potential), the U.S. Appalachia[1] region is expected to be an important source for the cellulosic biomass required to meet national renewable energy goals. A pilot-scale plant for producing ethanol from switchgrass is currently operating in Vonore, Tennessee [27]; the University of Tennessee has long been a part of the BFDP research program, and the program itself was initiated at Oak Ridge National Laboratory in Tennessee [80]. Thus, the state is a relevant location for this study.

Tennessee is not a dominant player (in terms of rank among U.S. states) when it comes to the supply of most major field crops. In 2010, the state ranked 27$^{\text{th}}$ in the value of field and miscellaneous crop production and 29$^{\text{th}}$ in the total value of principal crops (which also includes fruits, nuts and commercial vegetables) [115]. In terms of the value of cropland in Tennessee, among the five states in the Appalachia region, average cropland value in Tennessee ranks fourth. Among the ten U.S. economic regions, average cropland value in Appalachia ranks fifth [113]. See Figures 24 and 25 in the appendix for a geospatial map of the value of crops produced in the US and Tennessee, respectively.

According to the 2007 Census of Agriculture, by commodity group, the value of grains, oilseeds, dry beans and dry peas produced in Tennessee ranked 26$^{\text{th}}$ in the nation, the value of cotton and cottonseed ranked 10$^{\text{th}}$ out of the 17 states which produce cotton, and the value of hay and other crops ranked 41$^{\text{st}}$ in the nation. With respect to the market value of hay and field crops (cotton, grains and oilseeds), Tennessee ranked in the bottom half when compared to the rest of the nation. However, the state ranked in the top half with respect to acres devoted toward crop production. Among the 17 cotton producing states, Tennessee ranked 6$^{\text{th}}$ in terms of acres planted, 24$^{\text{th}}$ in land planted to wheat, 19$^{\text{th}}$ in land planted to corn, 17$^{\text{th}}$ in land planted to soybeans and 12$^{\text{th}}$ in land used for hay and other forage [112].

[1] The Appalachia region consists of Kentucky, North Carolina, Tennessee, Virginia and West Virginia.

Near-term challenges to meeting next-generation biofuel goals—which include costly feedstocks and encouraging farmer participation—make Tennessee an interesting case study. The combination of high bioenergy feedstock yields and relatively low value to traditional agricultural production could make the state a candidate for regional concentration of bioenergy feedstock supply.

The remainder of this chapter is organized as follows: in Section 4.2 we briefly introduce and discuss several models which have been used to estimate feedstock supply and the resultant impacts on agriculture and the environment; Section 4.3 describes the data sources and methodology used in developing switchgrass supply curves as well as crop displacement curves for Tennessee; Section 4.4 presents the supply curves and discusses them in the context of previous modeling efforts; concluding remarks are presented in Section 4.5.

## 4.2 Literature Review

Perlack et al. [89] produced one of the first studies estimating the potential supply of biomass feedstock for bioenergy production. This study considered supply based on technical feasibility. Since then, many studies have been conducted to estimate supply based on economic feasibility. Four economic models, FAPRI, FASOM, GTAP, and POLYSYS, have been particularly influential in both informing and evaluating agricultural and energy policy as it relates to the economic costs of large-scale production of biofuels and its resultant impact on the agricultural landscape.

The Food and Agricultural Policy Research Institute (FAPRI) model was developed by the joint research program between the Center for Agricultural and Rural Development (CARD) at Iowa State University and the Center for National Food and Agricultural Policy (CNFAP) at the University of Missouri. The FAPRI model is a partial equilibrium model which uses extensive data from the world agricultural market to develop baseline projections of the U.S. agricultural sector as well as international commodity markets [42]. The FAPRI/CARD International Ethanol Market Model extends the FAPRI model to include projections of "the production, use, stocks, prices, and trade for ethanol for several countries and regions of the world" [43]. Studies employing the model to evaluate bioenergy production include [41], which considers the global impact of local land allocation decisions in response to expanding ethanol production; and [56], which considers biofuel expansion under four policy/energy price scenarios and the resultant impact on agricultural commodities.

The Forest and Agricultural Sector Optimization Model (FASOM), developed by Bruce McCarl and his team at Texas A&M University, is a partial equilibrium model which simulates land allocation responses to policy in the forest and agricultural sectors. Simulation results depict the land allocation in each period which maximizes the net present value of total welfare—the sum of consumer and producer surplus [13]. With respect to biofuel production, the model has been used to assess market impacts of changes in demand for biomass feedstocks as well as the impact of meeting the renewable fuel targets set forth in the Energy Independence and Security Act of 2007 [13].

The Policy Analysis System (POLYSYS) is also a partial equilibrium model which has been used frequently to assess the impacts of biofuel production on agriculture and the environment. In fact, the technical feasibility report by Perlack et al. [89] was updated by Downing et al. [32] to consider economic potential using the POLYSYS model. The national simulation model analyzes deviations from a baseline projection of the U.S. agricultural sector in response to changes in policy as well as changes in economic or environmental conditions [28]. POLYSYS is composed of modules linking national supply, demand and prices for crops and livestock with national income. Additional modules, such as the energy crop module, have been developed to increase the scope of analysis. POLYSYS has been adapted to estimate potential biomass feedstock supply under various feedstock demand and price scenarios. After setting an exogenously determined price and level of demand for biomass feedstocks, a linear program is enacted for each of the models 305 regions—based on Agricultural Statistics Districts (ASDs)—to determine the land allocated to competing crops which maximizes the expected net present value of returns, subject to various constraints [28]. The group of researchers affiliated with the University of Tennessee's Agricultural Policy Analysis Center, where POLYSYS was developed, have used the model to produce a number of reports on the economic impacts of biofuels and the implications for agricultural land use. These studies can be found in [29, 31, 120, 121], among others.

The Global Trade Analysis Project (GTAP) is a global network of researchers and policy makers, a database, and a computable general equilibrium modeling framework. With its heavy focus on international trade, the general equilibrium model has been adapted and used extensively to study a number of economic and policy issues with global implications. The energy and environmental version of the model, along with land use, biofuel and greenhouse gas emission extensions to the GTAP database, have permitted a number of applications with particular focus on the global implications of biofuels. Applications to research on energy and the environment abound [51]; the GTAP Working Paper Series maintains a collection of research reports in progress which employ the GTAP model [52].

For a review of studies which integrate bioenergy systems into partial and general equilibrium models see Kretschmer and Peterson [65], Gerber et al. [48], and Birur et al. [14]. For a comprehensive review of the impacts of biofuels found in studies from the policy, environmental and economic literature, see Rajagopal and Zilberman [93].

These equilibrium models are particularly well suited to illustrate the linkages between economic sectors and the mechanisms through which decisions in one sector impact state variables and decisions in other sectors. However, as these models were developed to provide insight into the long-term implications of various policies or shocks to the system, they are limited in their ability to address many of the challenges impeding near term adoption of next-generation biofuels. For example, the models project changes in the agricultural landscape and commodity prices over long periods when the system is forced to meet target production levels. Yet, as is evident from the drastic reduction in 2011 mandated levels of cellulosic biofuel production from 250 million gallons to 6.6 million gallons, supply does not just appear in the appropriate quantities because a policy is put in place [119]. Thus, studies regarding how biofuel mandates will be met require greater resolution. Taking a narrower approach to the question of where biomass feedstock and biofuels will be produced—especially as it pertains to the near term challenges of getting the industry off the ground—and building on those results, may provide a better perspective on how policies can be achieved and the subsequent effect on the agricultural landscape.

Rajagopal et al. [92] note the increased complexity in a farmer's decision to adopt a new bioenergy crop. The adoption of next-generation biofuel technologies will require new markets and institutions. The risks involved create a "chicken-and-egg" problem of sorts. Farmers won't adopt these new crops unless they are guaranteed a market for their sale (via contracts) and returns at least as great as alternative uses for the land. Similarly, biorefineries will not come on board unless they can guarantee affordable year round feedstock supply, not to mention a market for their output, the necessary infrastructure to transport biofuels and policies which support the industry. Alexander et al. [6] discuss the challenges of contracting for perennial crops using principles from modern contract theory as a backdrop.

In the near and medium-term, before spot markets exist for the supply and purchase of cellulosic bioenergy feedstocks, the construction of biorefineries will drive the location of feedstock production and the prices at which feedstock will be available for purchase. Therefore, long-term projections of cellulosic feedstock supply should be done in tandem with biorefinery siting. Local projections of feedstock supply will aid the facility siting problem which will, in turn, facilitate better projections at the national and international scales.

The contributions of this chapter are to that effect. In focusing on the decision to adopt cellulosic feedstock at the county level, and paying particular attention to the importance of payment structure, variability in feedstock yields and assumptions on the commercial scalability of feedstock production, we hope to provide a refined approach to the estimation of feedstock supply and impacts on the agricultural landscape which will aid in the decision of where to locate facilities for biofuel production.

The aforementioned equilibrium models are not the only models which consider the economic competitiveness of bioenergy feedstocks and traditional commodity crops. A committee recently convened by the National Research Council used the Biofuel Breakeven model (BioBreak) to assess the feasibility of local or regional markets for cellulosic biomass [85]. Taking into account the full cost of producing and delivering biomass feedstock, as well as the potential revenue and full costs of producing biofuels from cellulosic feedstocks, the model calculates a biorefinery's "willingness to pay" for feedstock as well as an agricultural producer's "willingness to accept." Willingness to pay is the maximum price a biorefinery could pay for delivered biomass feedstock, without incurring losses. Willingness to accept is the minimum price an agricultural producer would accept for biomass; it is the price at which all costs are recouped. The model provides an excellent account of the costs associated with biofuel production; it is one of the few models which estimates feedstock costs including both transportation and storage costs.[2] However, breakeven models provide no insight into how agricultural producers decide to allocate land among competing endeavors. A method for determining how much land will be allocated to biomass feedstocks at various prices is essential in estimating the potential supply availability.

Khanna et al. employ the Biofuel and Environmental Policy Analysis Model

[2]Most studies only consider farm gate prices.

(BEPAM), an equilibrium model, in their study of the regional production of cellulosic feedstock. The model determines an economically viable mix of cellulosic feedstocks using a rolling horizon approach with 10-year planning period [64]. The model keeps the price of biomass constant over a period longer than two decades; yields of perennial grasses, like switchgrass, do not vary by soil or land quality (marginal land is assumed to produce the same yields as productive cropland); and the model imposes an arbitrary cap (25%) on the amount of land that can be converted to perennial grasses "due to concerns about the impact of monocultures" [64]. The model also uses historical crop mixes with small allowances (10%) for the production of new crops, to limit the cropland available for conversion to feedstock production [24].

Key assumptions highlighted above could have important implications for the actual willingness to produce biomass feedstock and the supplies available from land allocated toward feedstock production. For example, it has been reported that yields of cellulosic feedstocks like switchgrass vary according to soil quality and field landscape (e.g. sloping versus level land) [27, 33, 80, 83]. However, the size of decision making entities precludes analyses with a sufficient spatial distribution of feedstock yields. BEPAM does not vary feedstock yields by land category (e.g. cropland, idled land, pastureland), let alone classifications within categories. And because allocation decisions are made at the Crop Reporting District (CRD) level, yields will only vary by blocks of counties at best.[3] From the perspective of a biorefinery, estimates of potential feedstock availability will have to take into account yield variability at a smaller scale.

Due to the challenges of transporting cellulosic feedstock, it is likely that trade will be restricted to specific geographic regions [85]. It may be the case that a major

[3]The CRD is analogous to the Agricultural Statistics District (ASD) unit used by POLYSYS. In FASOM, land allocation decisions are made at either a 63 agricultural subregion scale or an 11 market region scale. FAPRI's U.S. model contains nine agricultural regions, and in GTAP the globe is apportioned into 18 agroecological zones.

transformation of the agricultural landscape takes place in one region of the country, rather than small transformations in all regions. Limiting the scale of adoption using historical crop mixes with small allowances for new energy crops, or arbitrarily imposing limits on the amount of cropland which could be converted, prevents study of the feasibility of such geographic concentration and its impact on the agricultural landscape. Therefore, in our case study we impose no limits on the amount of land that can be converted to switchgrass production. Our analysis provides insight into the conditions under which an "energy plantation"[4] might be formed and the resulting agricultural landscape.

Projections in these studies rely on energy crop yields obtained in field trials or through simulation models. However, not much is known about growing energy crops on a scale large enough to support a commercial biofuel industry [85]. It is not clear whether the yields attainable in small field trials—under ideal management practices and controlled conditions—will translate when production is at a much larger scale. And, as noted in [64, 85], increased cultivation could make energy crops more susceptible to pests and disease. Because we use a nonlinear production function, as opposed to the linear (Leontief) production functions used by BEPAM and other models, we can incorporate the effects of monoculture, or the inability of feedstock production to scale commercially, into the land allocation decision without imposing arbitrary constraints.

Parker et al. [86] develop a biofuel supply curve for the Western United States using the National Biorefinery Siting Model (NBSM), a model that combines mixed-integer linear optimization with a geographic information system (GIS). Designed to optimize the entire biofuel supply chain, the model:

> consider[s] explicit spatial distributions of biomass supply, competition

[4]This term has been adapted from Rajagopal et al. [92].

> among technologies for resources, and the economies of scale of conversion technologies in finding the best design for biofuel supply chains. The model locates, sizes, and allocates feedstock to biorefineries with the objective of maximizing the profitability of the industry as a whole [86].

The optimal location and size of a biorefinery will depend largely on the potential supply of feedstock. However, NBSM uses production statistics and FAPRI projections to determine the potential supply of energy and commodity crops. And, it assumes energy crops will be grown on marginal land only. Because the model's emphasis is on facility siting, it takes the variety and supply of feedstocks as given.

Graham et al. [54] also employ GIS modeling in their estimation of the costs of energy crops. Their goal is similar to ours in that they seek to evaluate the cost and supply of bioenergy feedstocks taking into account regional geographic variation. They also use Tennessee, and ten other states, as a test case. Nevertheless, their approach to estimating the land that will be converted to feedstock production, and thus the supply of feedstock, differs from the approach we employ here. They assume land is converted to feedstock production if the farm gate price is such that the net present value of producing feedstock is equivalent to what can be earned if the current mix of crops was maintained over the lifespan of the energy crop. The amount of land that would be converted is restricted to the amount of land dedicated to the dominant crop in their area in an optimistic scenario, or to the amount of land dedicated to minor crops in a pessimistic scenario. Their farm gate price is analogous to the minimum acceptable contract price in our model; however, the amount of land converted for feedstock production in our model is the optimal allocation between the current mix of commodity crops and feedstock production. Also, because the model uses annualized yields for energy crops in determining the price at which land is converted, it does not take into account the significance of the time value of money in prematurity years when yields are low but maintenance costs are still incurred.

Our approach focuses on the importance of yield variability, commercial scalability, and payment structure in estimating the potential supply of energy crops and in assessing their impact on the agricultural landscape via the crops they displace. By considering land allocation at the county level, our results and analysis are useful in deciding where to locate biorefineries. And, by not imposing arbitrary limits on the amount of land that can be converted to switchgrass production, we consider the cost and agricultural landscape associated with regional concentration of energy crop production.

## 4.3 Data and Methods

In estimating potential switchgrass production and crop displacement in the state of Tennessee, we modify the model developed in Chapter 2 to include multiple periods and the opportunity cost of land. The farmer faced with the option of growing switchgrass under contract for $T$ years will accept the offer if the contract price is such that expected profit under the optimal allocation of land between commodity and energy crop production is at least as great as expected profit over the $T$-year period from commodity crop production alone. Expected profits must also be greater than what is expected from the next best use of the farmer's land (opportunity cost).[5]

#### *4.3.0.1 Wholesale Contract*

Under wholesale contract, each farmer allocates land toward commodity crop production ($L_1$), switchgrass production ($L_2$), and the next the best opportunity ($L_3$) in order to maximize the expected net present value of profits over the $T$-year period,

[5]Keeping with the convention in the agricultural literature, we use the cash rental rate to reflect the opportunity cost of land.

as expressed in Equation (37).

$$E[\Pi_F^W]_{NPV} = \sum_{t=0}^{T-1} \left\{ \begin{array}{l} \left[\frac{p_{t+1}(1+g_y)^{t+1}}{(1+r)^{t+1}}\right] f_1(L_1) - \left[\frac{(1+g_c)^t}{(1+r)^t}\right] c_1 L_1 \\ \\ + \left[\frac{y_{M,t+1}}{(1+r)^{t+1}}\right] \omega f_2(L_2) - \left[\frac{c_{2t}}{(1+r)^t}\right] L_2 + \left[\frac{1}{(1+r)^{t+1}}\right] c_R L_3 \end{array} \right. \tag{37}$$

Where, $p_{t+1}$ is the expected spot price in year $t+1$; $g_y$ is the expected annual growth in commodity yields; $g_c$ is the expected annual growth rate of variable costs; $c_1$ is the variable (per unit land) cost of growing commodities at $t = 0$, $y_{M,t+1}$ is the switchgrass yield in year $t+1$ represented as a fraction of the yield at maturity (we assume stands reach maturity in year 3); $c_{2t}$ is the variable (per unit land) production cost for switchgrass in year $t$;[6] $\omega$ is the contract price (dollars per unit biomass); $c_R$ is the cash rental rate; and $r$ is the real discount rate. We assume all costs are incurred at the beginning of the year while payments are received at the end of the year.[7]

#### *4.3.0.2 Capacity Procurement Contract*

Under capacity procurement contract, each farmer allocates land toward the competing endeavors to maximize the expected profit in Equation (38).

$$E[\Pi_F^{CP}]_{NPV} = \sum_{t=0}^{T-1} \left\{ \begin{array}{l} \left[\frac{p_{t+1}(1+g_y)^{t+1}}{(1+r)^{t+1}}\right] f_1(L_1) - \left[\frac{(1+g_c)^t}{(1+r)^t}\right] c_1 L_1 \\ \\ + \left[\frac{\omega}{(1+r)^{t+1}}\right] L_2 - \left[\frac{c_{2t}}{(1+r)^t}\right] L_2 + \left[\frac{1}{(1+r)^{t+1}}\right] c_R L_3 \end{array} \right. \tag{38}$$

As with the wholesale contract, we assume all revenues are earned at the end of the year while costs are incurred at the beginning. Here, the contract price $\omega$ has unit dollars per (land) area.

[6] $c_{2,0}$ represents establishment costs per unit land, $c_{2t}$, for $t > 0$ are annual maintenance and harvest costs.

[7] For crops that are harvested more than once a year, costs have been annualized.

#### 4.3.0.3 Minimum Expected Profit Under Contract

The farmer will only accept a contract (wholesale or capacity procurement) if the price is such that expected profit under contract is at least as great as expected profit from commodity production and/or the next best alternative over the $T$-year horizon. In other words, expected profit under contract must be greater or equal to:

$$E[\Pi_F^{NC}]_{NPV} = \max_{L_1,L_3} \sum_{t=0}^{T-1} \frac{p_{t+1} f_1(L_1)(1+g_y)^{t+1}}{(1+r)^{t+1}} - \frac{c_1(1+g_c)^t L_1}{(1+r)^t} + \frac{c_R L_3}{(1+r)^{t+1}}$$
$$\text{s.t.} \quad L_1 + L_3 = L \tag{39}$$

### 4.3.1 Data

To calibrate the model, we make use of the following sources for data and parameter estimates: USDA National Agricultural Statistical Service (NASS) [114], field crop budgets created by the University of Tennessee [79], and a study on switchgrass production in Tennessee by Mooney et al. (2009) [83]. From NASS we obtained the following data for major grains and field crops produced in Tennessee: land planted, land harvested, yield, and total production. The data are available annually for each county in the state. Crop budgets are produced annually by the University of Tennessee as a short-term (annual or less) planning tool. For select crops (corn, cotton, soybeans, wheat and hay) and farming practices (e.g. conventional tillage, no tillage), crop budgets provide per acre estimates of the variable and fixed costs of field operations required to achieve a given crop yield. Budgets also contain an estimated market price for each crop. Mooney et al. analyze data from a three year experiment of switchgrass production on lands of varying quality/suitability [83]. The paper contains production budgets similar to the crop budgets produced by the University of Tennessee as well as five- and ten year projections of switchgrass yields based on the experiments.

#### 4.3.1.1 Calibrating the Model

Our model is calibrated at the crop-county level; this is the lowest level of aggregation for which data are available. The data are presented such that crop production is completely separable. Therefore, we assume that in each county, a crop is produced by a single enterprise. In other words, we assume a single farmer produces all of the, say, corn in a given county, and no other crops.[8] Parameters of the production function are estimated from the yields reported in NASS for commodity (food) crops and those reported in Mooney et al. for switchgrass. Production costs and expected prices for commodity crops were obtained from the crop budgets, while switchgrass production costs were obtained from [83]. Following Mooney et al., a real discount rate of 5.4% was used to discount cash flows. The following snapshots of data tables will help illustrate the parameter estimation process for crop production functions.

Table 7: Snapshot of NASS Report for Cotton Production in Tennessee

| County | District | Planted All Purposes (acres) | Harvested (acres) | Yield (lbs/acre) | Production (bales) |
|---|---|---|---|---|---|
| Dyer | 10 | 25,600 | 24,800 | 823 | 42,500 |
| Carroll | 20 | 24,900 | 24,700 | 865 | 44,500 |

We use the NASS data (Table 7) to calibrate the crop production function $f_1^{ik}(L_1^{ik}) \equiv (\beta_1^{ik} - \delta_1^{ik} L_1^{ik}) L_1^{ik}$ for each commodity crop $i \in I$, in each county $k \in K$. The discrepancy between acres planted and acres harvested include losses due to crop failure and summer fallow—the soil conservation practice of moisture preservation. Crop failure typically claims 2–3% of planted acres while the practice of summer fallow has been

[8]The cash rental rate reflects average returns to agricultural lands. So while we assume the farmer produces only a single crop, the decision to allocate land toward the next best alternative can indicate the desire to grow an alternative commodity crop.

largely replaced by no-tillage and other soil conservation techniques [110]. Therefore, in this context, $\delta_1^{ik}$ reflects the yield reduction due to the typical occurrence of crop failure, while $\beta_1^{ik}$ reflects yield in the absence of crop failure. Since commodity crop production is mature, we set $\beta_1^{ik} = 1.01y^{ik}$, where $y^{ik}$ is the NASS reported yield (column 5 of Table 7). In other words, we assume that in the absence of crop failure, yields would be 1 percent greater than what was reported. We choose $\delta_1^{ik}$ to satisfy the following equation: $y^{ik}\check{L}^{ik} = (\beta_1^{ik} - \delta_1^{ik}\check{L}^{ik})\check{L}^{ik}$, where $\check{L}^{ik}$ is the land planted to crop $i$ in county $k$ (column 3). This calibration method ensures that our production functions provide estimates consistent with the observed data.

To prevent double counting of the total land available due to the practice of double cropping[9] soybeans and wheat, we assume all counties which planted acres to both soybeans and wheat engaged in double cropping; therefore, this may undercount land somewhat. Let $K^{DC}$ denote the set of counties which planted acres to both wheat and soybeans, $L_1^{wheat,k}$ denote the land planted to wheat in county $k$ (as reported in NASS), and $L_1^{soy,k}$ denote the land planted to soybeans in county $k$. Then for each county $k \in K^{DC}$, we assume the amount of land double cropped with soybeans and wheat, $L_1^{\mathrm{WS}k}$, the land planted to soybeans under traditional practices (i.e. acres that are not double cropped but planted solely to soybeans), $L_1^{sk}$, and the land planted to

[9]Double cropping is the practice of growing two crops on the same tract of land during a single growing season. The NASS database provides the total amount of land planted to a crop without differentiating between double cropping or traditional practices.

wheat under traditional practices, $L_1^{wk}$, are as follows:

$$L_1^{\mathrm{WS}k} = \begin{cases} L_1^{wheat,k} & \text{if } L_1^{wheat,k} \leq L_1^{soy,k}, \\ L_1^{soy,k} & \text{if } L_1^{wheat,k} > L_1^{soy,k} \end{cases}$$

$$L_1^{sk} = \begin{cases} L_1^{soy,k} - L_1^{\mathrm{WS}k} & \text{if } L_1^{wheat,k} \leq L_1^{soy,k}, \\ 0 & \text{if } L_1^{wheat,k} > L_1^{soy,k} \end{cases}$$

$$L_1^{wk} = \begin{cases} 0 & \text{if } L_1^{wheat,k} \leq L_1^{soy,k}, \\ L_1^{wheat,k} - L_1^{\mathrm{WS}k} & \text{if } L_1^{wheat,k} > L_1^{soy,k} \end{cases} \tag{40}$$

Switchgrass yields in Western Tennessee vary according to the productivity of the land on which it is grown [83]. To approximate switchgrass production in each county, we make several assumptions regarding the quality of land used to grow each crop, then use the experimental results in Table 8 to calibrate the switchgrass production function: $f_2^{ik}(L_2^{ik}) \equiv (\beta_2^{ik} - \delta_2^{ik} L_2^{ik}) L_2^{ik}$. We use the superscript $ik$ to indicate that switchgrass will be grown in county $k$ on land currently used in producing commodity crop $i$. The four experimental switchgrass locations, denoted WDLU (moderately well drained level upland), WDFP (well- to moderately well-drained flood plain), MDSU (moderate to somewhat poorly drained eroded sloping upland) and PDFP (poorly drained flood plain), are characteristic of the physiogeographic landscape in West Tennessee [83].

> The WDLU and WDFP locations represented high-yielding environments suitable for row crop production. ... The less-well-drained MDSU and PDFP locations represented intermediate and marginal yield environments, respectively, ... The MDSU landscape, in particular, is representative of over half the farmland in West Tennessee, and is considered to be the most likely production environment for switchgrass produced as

a bioenergy crop in the region [83].

Table 8: Snapshot of Switchgrass Dry Matter Yields Reported in Mooney et al. (2009)

| | Experiment Location† | | | |
|---|---|---|---|---|
| | WDFP | WDLU | PDFP | MDSU |
| | | Mg ha$^{-1}$ | | |
| **2004** | | | | |
| Mean | 2.37 | 2.96 | 1.59 | 2.22 |
| SD | 1.21 | 1.12 | 0.81 | 0.63 |
| Min. | 0.83 | 0.72 | 0.25 | 1.25 |
| Max. | 4.73 | 4.91 | 2.80 | 3.54 |
| **2005** | | | | |
| Mean | 11.13 | 11.65 | 6.74 | 8.89 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| **2006** | | | | |
| Mean | 15.59 | 22.87 | 10.55 | 17.96 |
| SD | 6.07 | 4.08 | 4.52 | 6.83 |
| Min. | 1.86 | 12.52 | 2.31 | 5.47 |
| Max. | 35.35 | 32.23 | 20.88 | 36.00 |

†WDFP=well to moderately well drained flood plain, WDLU=moderately well drained level upland, PDFP= poorly drained flood plain, and MDSU=moderately to somewhat poorly drained eroded sloping upland.

We assume the same physiogeographic conditions extend to the entire state and classify the productivity of the land planted to each crop in each county by the yields reported in NASS. Specifically, for each commodity crop $i$ we order all counties from lowest yield ($y_i^{(1)}$), to greatest ($y_i^{(K)}$). Counties with yields less than or equal to the median yield ($y_i^{(1/2K)}$) are assumed to have devoted land of productivity (quality) similar to MDSU toward production of that crop. In other words, counties with the lowest yields are assumed to have planted their crop on lower quality (less productive) land. We use $y_i^{(3/4K)}$, the median crop yield in $[y_i^{(1/2K)}, y_i^{(K)}]$, as the cutoff between land of quality WDFP and WDLU. See Figure 12 for an illustration. According to [83], the PDFP category is for marginal land characteristic of that which qualifies for the USDA Conservation Reserve Program. Therefore, we assume none of the commodities reported in NASS would have been grown on land of that quality. In our sensitivity analysis we evaluate the impact of this classification method on model results.

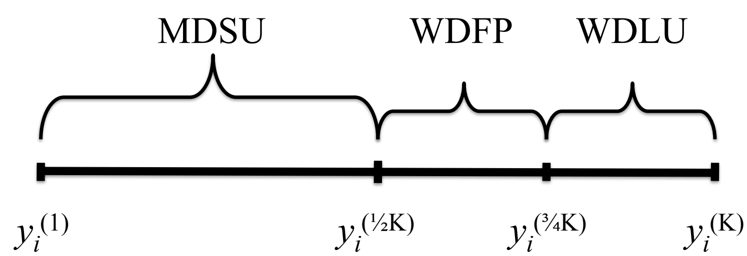



Figure 12: Soil Classification Rule

Since switchgrass stands typically reach maturity by year three [83, 85], we set $\beta_2^{ik}$ for each land productivity category equal to the reported mean in 2006 for that land type (Table 8). For example, the land used to grow cotton in Dyer county (Table 7) was classified as MDSU based on its relative yield. Therefore, we set $\beta_2^{cot,Dyer}$ to 17.96 Mg/ha (8.01 tons/acre). Let $K^{ij}$ denote the set of counties $k$ which used land of quality $j \in \{\text{WDLU}, \text{WDFP}, \text{MDSU}\}$ to grow commodity $i$. As an estimate of $\delta_2^{ik}$ on land of productivity $j$ growing crop $i$, we take the average of the $\delta_1^{ik}$ $\forall k \in K^{ij}$. Continuing with our cotton example,

$$\delta_2^{cot,Dyer} = \frac{\sum\limits_{k \in K^{cot,\text{MDSU}}} \delta_1^{cot,k}}{n(K^{cot,\text{MDSU}})}$$

where $n(K^{cot,\text{MDSU}})$ is the number of counties growing cotton on land classified as MDSU. We assume the yield reduction rate for switchgrass is on par with that of the commodity it is displacing, meaning it experiences the same typical rate of crop failure. The implication of this assumption is that switchgrass yields are fully scalable in our baseline scenario. Later we relax this assumption to consider what happens when the yields attainable in the field experiments do not scale with larger field sizes.

The switchgrass production cost, per unit land, was derived from the "cost-minimizing treatment combination" and estimated harvest costs provided in [83].[10] Table 9 lists the switchgrass costs (in 2010 dollars) and yields used for our baseline scenario.

Table 9: Yield and Cost Parameters for Switchgrass Production by Land Type. (1) Fraction of maturity yield harvestable in year one. (2) Fraction of maturity yield harvestable in year two. Prematurity year yields were derived from the 2004 and 2005 mean yields reported in [83] (Table 8).

| Site | Establishment Cost $/acre | Annual Maintenance Cost $/acre | Yield at Maturity tons/acre | Year One$^{(1)}$ Yield | Year Two$^{(2)}$ Yield |
|---|---|---|---|---|---|
| WDLU | 158 | 255 | 10 | 13% | 51% |
| WDFP | 213 | 203 | 7 | 15% | 71% |
| MDSU | 158 | 235 | 8 | 12% | 50% |

To determine expected profit in the absence of a switchgrass contract over the $T$-year horizon for each enterprise in each county (Problem (39) in Section 4.3.0.3) we require expected prices and costs over the period, as well as yield and cost growth rates. As the year one price for each crop we use the price estimate provided in the *Field Crop Budgets for 2011* [79] (see Table 10 for an example). For each subsequent year, we use a 3-year lag expectation over the prices received by Tennessee farmers during the period from 2008 to 2010. Prices were obtained from the *USDA Crop*

[10] According to [83], establishment costs were based on the seeding rate, while annual maintenance costs were based on nitrogen applications. The study reports the cost of each seeding treatment (five total) and each nitrogen treatment (four total) tested, as well as the cost minimizing seeding and nitrogen rate combination. Harvest cost estimates were based on the projected dry matter yield at each site.

Table 10: Snapshot of 2010 Crop Budget for Cotton Production

| COTTON, ROUNDUP READY FLEX - CONVENTIONAL TILLAGE, 850 POUND YIELD ESTIMATED RETURNS AND EXPENSES PER ACRE, (12/16ROW EQUIPMENT)) | | | | | |
|---|---|---|---|---|---|
| ITEM | DESCRIPTION | UNIT | QUANTITY | PRICE | AMOUNT |
| REVENUE | | | | | |
| COTTON(1)(2)(7) | Lint | LB. | 850 | \$0.69 | \$586.50 |
| VARIABLE EXPENSES | | | | | |
| SEED (3) | 3.5 SEEDS/FOOT | THOUS | 48.145 | \$0.60 | \$28.89 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| MACHINERY EXPENSES | | | | | |
| MACHINERY DEPRECIATION | | AC. | 1 | \$54.23 | \$54.23 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| LABOR EXPENSES | | | | | |
| LABOR | | HR. | 1.76 | \$9.75 | \$17.20 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |

*Values 2010 Summary* [115]; the lag expectation, $p_t = 0.5p_{2010} + 0.3p_{2009} + 0.2p_{2008}$, was adapted from [94]. Production costs, both fixed and variable, were also obtained from the crop budgets; we take the average of all cropping practices (e.g. tillage and no tillage).[11] The rental rate for cropland in each county was obtained from *Tennessee Cash Rents, 2010* [111]. All prices and costs were converted to 2010 dollars using the consumer price index [17]. Yield and cost growth rates were calculated from *USDA Agricultural Projections to 2020* [116]. We assume the total cropland available is that which was planted to all purposes in 2010 as reported in NASS (column 3 of Table 7); in other words, $L = \check{L}^{ik}$. Table 11 lists parameter values for commodity crops in the baseline scenario.

### 4.3.2 Switchgrass Supply and Cropland Displacement

We develop switchgrass supply curves, under each contract structure, by first determining the amount of cropland that could be converted to switchgrass production, then calculating total supply using the switchgrass production functions. Given a contract price, each farm enterprise (crop-county pair) allocates land in order to

[11]The NASS database did not distinguish between cropping practices for production in Tennessee so we averaged the costs under both cropping practices.

Table 11: Price, Yield and Cost Parameters for Commodity Crops. (1) NASS only contains data on harvested acres; costs were derived from the field crop budget for Winter Annuals Hay, excluding planting costs. Year One price reflects the average breakeven price from the budget. (2) A portion of the wheat grown in Tennessee is double cropped with soybeans [59]. In our analysis we assume all counties which grew both wheat and soybeans double cropped. Production costs for double cropped wheat and soy were estimated as one-half of the costs common to both crops plus crop specific costs (e.g. crop seeds).

| Crop | Expected Yield | | Production Cost | | Year One Price | | 3-yr Lag Expectation | |
|---|---|---|---|---|---|---|---|---|
| Corn (High Yield) | 150 | bu/acre | 375.43 | \$/acre | 4.85 | \$/bu | 4.46 | \$/bu |
| Corn (Low Yield) | 120 | bu/acre | 309.41 | \$/acre | 4.85 | \$/bu | 4.46 | \$/bu |
| Cotton | 850 | lbs/acre | 502.56 | \$/acre | 0.85 | \$/lb | 0.72 | \$/lb |
| Soybeans | 40 | bu/acre | 231.40 | \$/acre | 10.75 | \$/bu | 10.68 | \$/bu |
| Wheat | 60 | bu/acre | 283.21 | \$/acre | 6.25 | \$/bu | 5.15 | \$/bu |
| Hay$^{(1)}$ | 2 | tons/acre | 66.92 | \$/acre | 101.82 | \$/ton | 81.59 | \$/ton |
| **Double Cropped:**$^{(2)}$ | | | | | | | | |
| Wheat | 60 | bu/acre | 240.47 | \$/acre | 6.25 | \$/bu | 5.15 | \$/bu |
| Soybeans | 30 | bu/acre | 229.52 | \$/acre | 10.75 | \$/bu | 10.68 | \$/bu |

maximize expected net present value of profits, Equations (37) and (38), subject to the land constraint $L_1 + L_2 + L_3 \leq L$. As in Chapter 2, we determine the minimum acceptable contract price that must be guaranteed over the $T$-year period such that profit while producing switchgrass is at least as great as expected profit over the $T$-year period from commodity production and/or the next best alternative $E[\Pi_F^{NC}]$, see Equation (39). Therefore, provided the contract price $\omega$ is at least as great as the minimum acceptable, we estimate the total cropland which could be converted to switchgrass production under wholesale contract as $L_2^W(\omega) \equiv \sum_{i \in I} \sum_{k \in K} L_2^{ik\star}(\omega)$, where $\forall i$, $\forall k$, $L_2^{ik\star}(\omega)$ is an element of:

$$\underset{L_1^{ik}, L_2^{ik}, L_3^{ik}}{\operatorname{argmax}} \sum_{t=0}^{T-1} \left\{ \begin{array}{l} \left[\dfrac{p_{t+1}^i (1+g_y^i)^{t+1}}{(1+r)^{t+1}}\right] f_1^{ik}(L_1^{ik}) - \left[\dfrac{(1+g_c^i)^t}{(1+r)^t}\right] c_1^i L_1^{ik} \\ \\ + \left[\dfrac{y_{M,t+1}^{ik}}{(1+r)^{t+1}}\right] \omega f_2(L_2^{ik}) - \left[\dfrac{c_{2t}^{ik}}{(1+r)^t}\right] L_2^{ik} \\ \\ + \left[\dfrac{1}{(1+r)^{t+1}}\right] c_R^k L_3^{ik} \end{array} \right.$$

$$\text{s.t.} \quad L_1^{ik} + L_2^{ik} + L_3^{ik} \leq \check{L}^{ik} \tag{41}$$

Conversion under capacity procurement contract is $L_2^{CP}(\omega) \equiv \sum_{i\in I} \sum_{k\in K} L_2^{ik\dagger}(\omega)$, where $\forall i$, $\forall k$, $L_2^{ik\dagger}(\omega)$ is an element of:

$$\underset{L_1^{ik},L_2^{ik},L_3^{ik}}{\operatorname{argmax}} \sum_{t=0}^{T-1} \left\{ \begin{aligned} & \left[\frac{p_{t+1}^i(1+g_y^i)^{t+1}}{(1+r)^{t+1}}\right] f_1^{ik}(L_1^{ik}) - \left[\frac{(1+g_c^i)^t}{(1+r)^t}\right] c_1^i L_1^{ik} \\ & + \left[\frac{\omega}{(1+r)^{t+1}}\right] L_2^{ik} - \left[\frac{c_{2t}^{ik}}{(1+r)^t}\right] L_2^{ik} \\ & + \left[\frac{1}{(1+r)^{t+1}}\right] c_R^k L_3^{ik} \end{aligned} \right.$$
$$\text{s.t.} \quad L_1^{ik} + L_2^{ik} + L_3^{ik} \leq \check{L}^{ik} \tag{42}$$

Note the land allocation decision is made only once at $t = 0$. We assume the contract locks in that land use for the full $T$ periods.[12] Realistically, the land allocated to commodity production, $L_1$, and the next best alternative, $L_3$, will change over the period as spot price expectations are updated. However, our focus is on the land converted to switchgrass production, and since we assume that decision is irreversible over the contract lifespan, we do not simulate changes in $L_1$ and $L_3$ as commodity prices and cash rental rates change over time. We also assume the contract offer is a one time, take-it-or-leave-it contract so that the farmer will not be offered a contract in any other period.

The expected supply of switchgrass at maturity is

$$Q_S^W(\omega) = \sum_{i\in I} \sum_{k\in K} \big(\beta_2^{ik} - \delta_2^{ik} L_2^{ik\star}(\omega)\big) L_2^{ik\star}(\omega), \text{ and}$$
$$Q_S^{CP}(\omega) = \sum_{i\in I} \sum_{k\in K} \Big(\beta_2^{ik} - \delta_2^{ik} L_2^{ik\dagger}(\omega)\Big) L_2^{ik\dagger}(\omega)$$

under wholesale contract and capacity procurement contract, respectively.

[12]Under capacity procurement the contract indeed makes the land allocation decision binding. Terms of the wholesale contract only specify payment on whatever is produced. However, since it takes several years for switchgrass stands to reach maturity it is reasonable to assume that for short horizons like the one we consider here, land conversion will not be reversed before the contract period ends.

## *4.4 Results and Discussion*

### 4.4.1 Initial Results

Our model assumes a 5 year contract period ($T = 5$) for switchgrass production. This length was chosen to be consistent with the production parameters obtained from [83] and to keep in line with our focus on near-term feasibility. There is still considerable uncertainty with respect to biofuel policies and technologies. In the midst of such uncertainty, a farmer or biorefinery might be reluctant to enter into a contractual arrangement with longer horizon. Summary results of our baseline scenario are depicted in Figures 13–15. Converted cropland under each contract structure, at varying contract prices, is illustrated in Figures 13 and 14. The corresponding supply of switchgrass, once stands have reached maturity, is illustrated in Figure 15.

In 2010, Tennessee planted 0.71 million acres of corn, 0.38 million acres of cotton,[13] 1.45 million acres of soybeans, 0.26 million acres of wheat, and harvested 1.95 million acres of hay [114]. A total of 4,529,900 acres (4.5 million acres) were planted to these five crops throughout the state, compared with 290 million acres devoted to these crops across the country. Using our method for estimating double cropped acres outlined in (40), we assume 1.2 million acres were planted to soybeans using traditional practice, 0.036 million acres of wheat were planted under traditional practice, and 0.22 million acres were double cropped.[14]

Under wholesale contract (Figure 13), a farm gate price of \$55/ton was sufficient to convert 14% of total cropland.[15] A majority of the land converted at that price (67%) was land used in harvesting hay. Switchgrass production was least competitive

[13] According to the 2010 State Agriculture Overview, 390,000 acres of cropland were used in planting cotton [112]. However, the NASS database only accounts for 384,400 of those acres.

[14] The expected soybean yield under double cropping is less than under traditional practice by 10 bushels per acre. The expected wheat yields are equivalent. Therefore, overestimating the amount of land used in double cropping would result in overestimating the total amount of land that would be converted to switchgrass (by underestimating soybean revenues). Similarly, underestimating the amount of land used in double cropping tends to underestimate the cropland that would be converted to switchgrass production.

[15] Prices at the farm gate do not include transportation or storage costs.

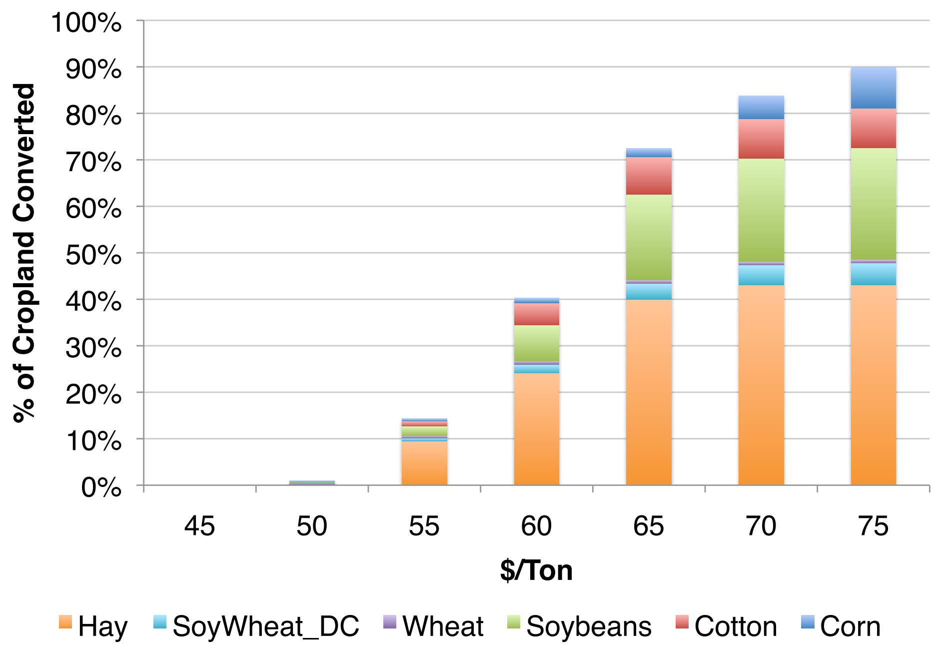



Figure 13: Fraction of total cropland converted to switchgrass production and the commodity crops they displace under a wholesale contract as a function of price for the Tennessee case study. SoyWheat_DC refers to double cropping of soybeans and wheat. Note that wheat planted under traditional practices comprises such a small share of cropland that it is faintly visible between soybeans and double cropped soybeans and wheat.

with corn, displacing less than 4% of its cropland at $55/ton and less than 32% at $70/ton. Switchgrass was most competitive with wheat, displacing more than 66% of its cropland at $55/ton and all of the land planted exclusively to wheat at $60/ton. Soybean production is quite profitable relative to wheat, so the displacement of land that was double cropped occurred at a rate slightly higher than soybean displacement. At $55/ton, 7.3% of the land growing soybeans under traditional practice was displaced and 12.6% of double cropped acres were displaced.

Under capacity procurement contract (Figure 14), a farm gate price of $350/acre was sufficient to convert 67% of total cropland. As under the wholesale contract structure, switchgrass was most competitive with wheat and least competitive with corn, displacing 100% and 6.97% of cropland, respectively, at $350/acre. Recall that maximum yields at maturity range from 7 tons/acre to 10 tons/acre, depending on the

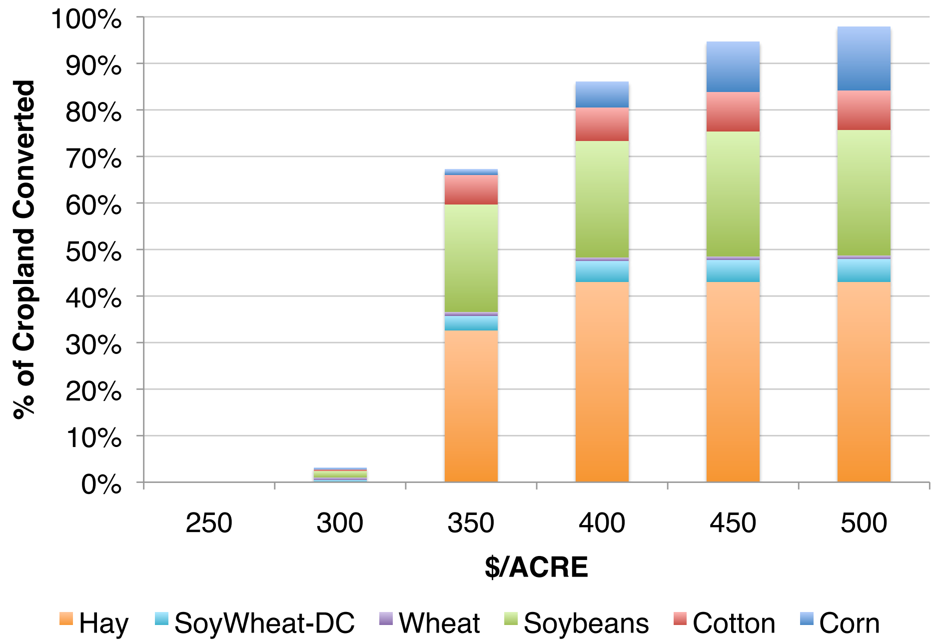



Figure 14: Fraction of total cropland converted to switchgrass production and the commodity crops they displace under a capacity procurement contract at various prices.

land productivity. Therefore, once stands reach maturity, the capacity procurement price of $350/acre yields average prices per ton which range from $39 to $54. The pre-maturity yields are an important factor in determining switchgrass conversion under wholesale contract. This point will be illustrated further in Section 4.4.2 when we discuss results from our sensitivity analysis.

Switchgrass supply curves are presented in Figure 15; the figure depicts dry tons available per year, once stands have reached maturity. The vertical axis on the right displays the wholesale price and corresponds to the triangle markers, while the axis to the left displays the capacity procurement prices which correspond to the square markers. At $55/ton, over six million dry tons of switchgrass are available under wholesale contract. At a capacity procurement price of $350/acre, over 23 million dry tons are available. To put this level of supply in perspective, at a conversion rate of 70 gallons cellulosic ethanol per dry ton, an ethanol biorefinery with a 50 million gallon per year (mmgy) capacity would require approximately 714,000 dry tons per

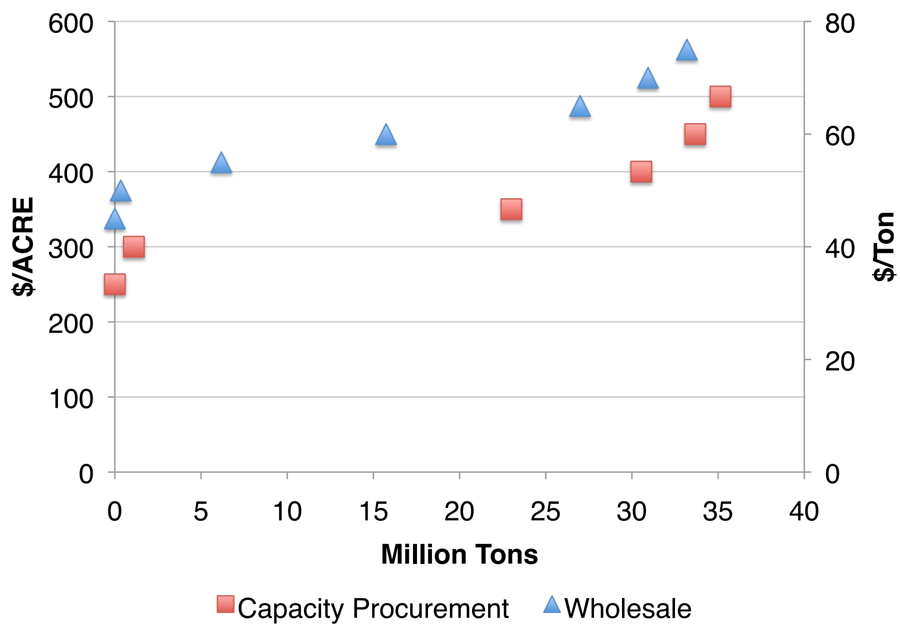



Figure 15: Switchgrass supply curves under capacity procurement and wholesale contracts for the Tennessee case study.

year; a biorefinery with a 100 mmgy capacity would require roughly 1.4 million dry tons annually.[16]

A demonstration scale cellulose-to-ethanol plant in Tennessee was reported to have a breakeven price for delivered feedstock (maximum willingness to pay for switchgrass that has been transported to the site) of \$83/Mg (\$76/ton in 2010 dollars) [83]. The pilot plant, which will use both switchgrass and corn cobs, has a capacity of 250,000 gallons per year [2]. A farm gate price of \$55/ton leaves about \$21/ton to cover transportation and storage costs. Literature estimates of switchgrass transportation costs range from \$14–\$36 per ton while storage estimates range from \$2–\$3 per ton (2007 dollars) [85].

Currently, the pilot plant has three-year contracts with farmers in surrounding counties, paying each \$450 per acre per year [57]. The price seems high, but the

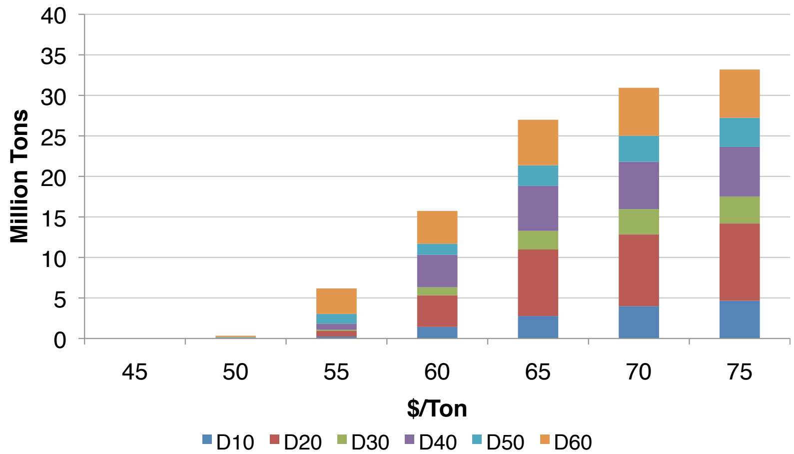
[16]These biorefinery capacities are typical of those in existence or under construction in the United States in 2010. The conversion rate is at the conservative end of rates reported in the literature [85].

group is conducting a number of experiments with management practices. Some explanation for the contract terms was provided by Kelly Tiller, president of Genera Energy, LLC—which has partnered with DuPont Danico Cellulosic Ethanol in this endeavor.

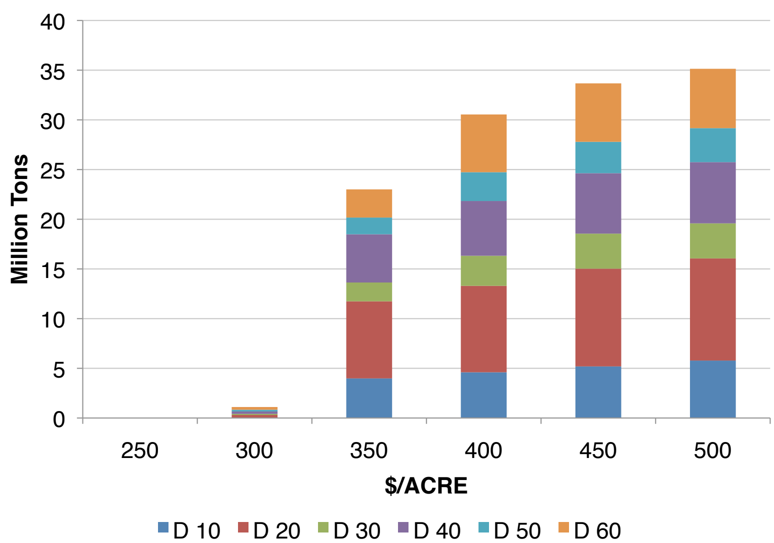
> Those types of experiments, especially those tinkering with yield, were part of the consideration of how and why Tiller and her colleagues arrived at the $450/year-for-three-years contract. "Price discovery is really difficult because it's just a very immature market—if there's even a market for switchgrass," she says. "We had to find ways to arrive at a price attractive enough for farmers to be willing to participate and take on any risks. We don't want the price so high it sends the wrong market signals or provides any kind of long-term consequence." Paying only based on tonnage or other volume amount wasn't going to make farmers happy or willing when researchers wanted to experiment on production practices affecting yield, Tiller says [57].

The estimated breakeven price (biorefinery willingness to pay) and actual contract price currently being offered provide a benchmark by which we can compare production potential across districts.

Switchgrass supply is presented by Agricultural Statistics District (ASD) in Figure 16. Under the wholesale contract structure, Figure 16(a), the majority of switchgrass available at lower contract prices is supplied by District 60, a district dominated by hay production. Once prices reach $65/ton most switchgrass available is supplied by District 20, the largest district in terms of available cropland. In contrast, under capacity procurement contract the lion's share of switchgrass supply is available from District 20 at every price, Figure 16(b). These results are consistent with those obtained in [54]. These two districts have the potential to supply a substantial amount of biomass feedstock, see Figure 17.

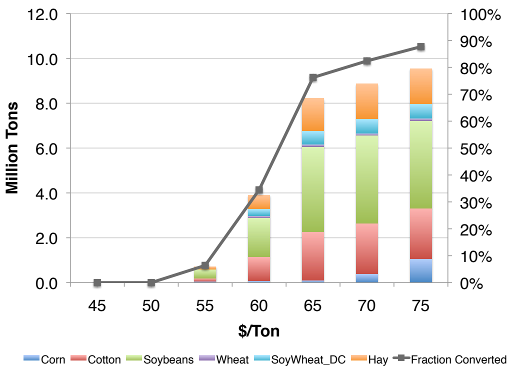



(a) Wholesale Contract

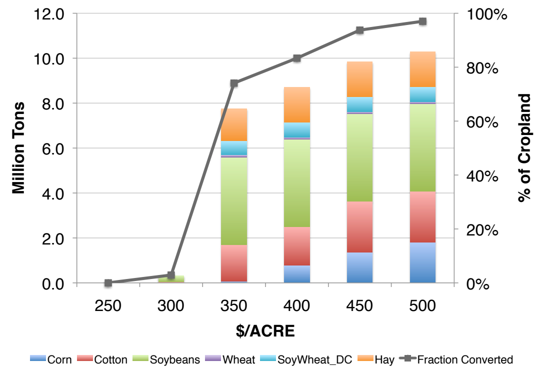



(b) Capacity Procurement Contract

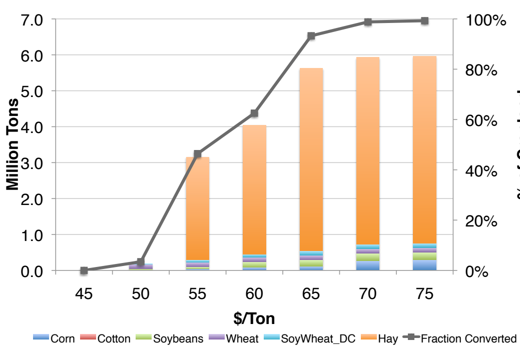
Figure 16: Switchgrass supply curves by district under (a) wholesale contract and (b) capacity procurement contract. Supply is based on maturity year yields.



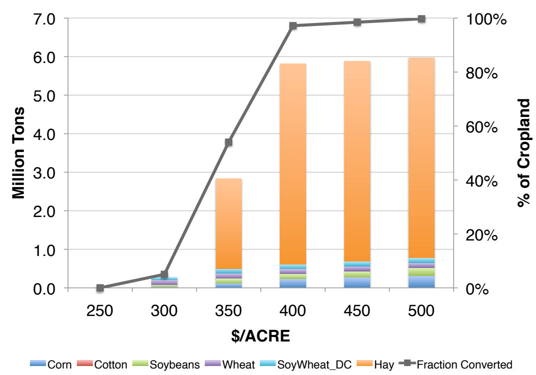

(a) District 20: Wholesale Contract




(b) District 20: Capacity Procurement Contract




(c) District 60: Wholesale Contract




(d) District 60: Capacity Procurement Contract

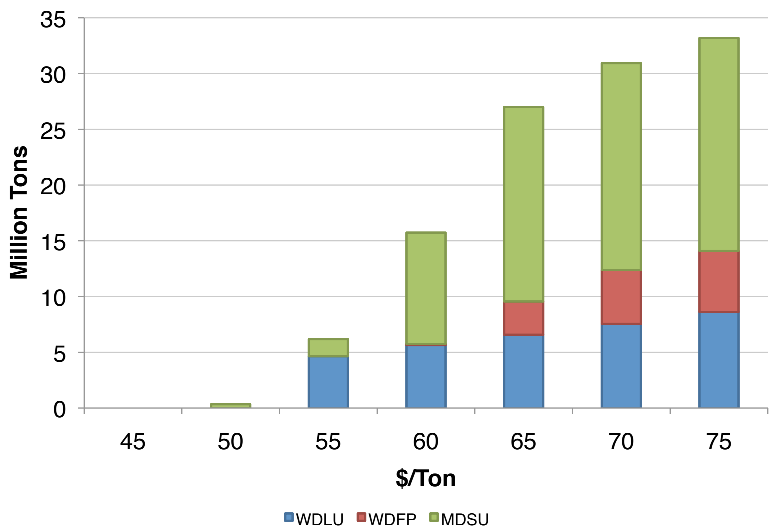
Figure 17: Available supply, fraction of cropland converted to switchgrass production, and the crops which would be displaced at various contract prices in Districts 20 and 60. Supply under wholesale contract is depicted in Figures (a) and (c) for Districts 20 and 60, respectively. Corresponding capacity procurement contracts are depicted in Figures (b) and (d). Columns indicate supply (left vertical axis) while square markers indicate the fraction of total district cropland converted in order to achieve the level of supply.

Profit margins on hay production are thin at average yields [1]. A considerable number of counties in District 60 achieve yields substantially greater than the average; however, the expected price of hay is low, making the crop vulnerable to displacement.[17] On the other hand, soybeans are the dominant crop in District 20, but all major crops are well represented. While there is substantial production of higher margin crops, yields in the district are low to moderate. Two-thirds of cropland is classified as MDSU, the lowest quality category we consider, and one quarter is classified WDFP, the mid level quality.

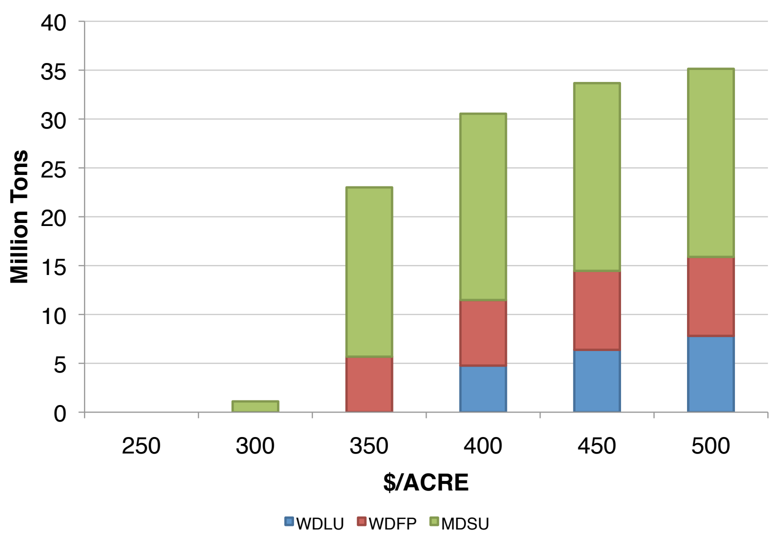
In District 20 a wholesale price of \$55/ton could secure 700,000 dry tons switchgrass, enough to supply a 50 mmgy ethanol biorefinery under the moderate conversion rate of 70 gallons per dry ton, displacing only 6% of total cropland in the district. At the more optimistic conversion rate of 90 gallons per dry ton, only 600,000 dry tons switchgrass would be required annually, displacing even fewer crops. In District 60, that wholesale price could secure over 3.1 million dry tons, more than enough to supply the 1.4 million dry tons a 100 mmgy ethanol biorefinery requires under the moderate conversion rate, or several 50 mmgy biorefineries depending on the geographic dispersion of available feedstock. However, siting several biorefineries may lead to higher contract prices if biorefineries must compete with commodity crop production and rival facilities.

Figure 18 illustrates the relationship between biomass feedstock adoption and land quality. Interestingly, contract structure plays an important role in the competitiveness of biomass feedstock production on lands of different productivities. At a wholesale price of \$55/ton, most of the cropland converted is of the highest quality, WDLU. The majority of this conversion comes from hay in District 60; however, a

[17]Despite the importance of hay, in terms of the value of Tennessee's agricultural production, there is no central market for its sale in the state. Price discovery is largely through word of mouth and a hay directory website. Compared with other commodity crops, little is known about the supply and demand relationship for hay [12].




(a) Wholesale Contract




(b) Capacity Procurement Contract

Figure 18: Switchgrass supply curves by land type under (a) wholesale contract and (b) capacity procurement contract. Supply is based on maturity year yields.

substantial amount of the highest yielding cropland growing cotton is also converted. Conversely, at a capacity procurement price of $350/acre only low, MDSU, and mid quality, WDFP, lands are converted. Roughly equal amounts of mid quality soybean and hay cropland is converted. All of the low quality cotton cropland is converted, and nearly all of the low quality cropland planted to soybeans, hay, and double cropped (soybeans and wheat) are converted.

The amortized cost of producing switchgrass on high quality land (productivity WDLU) is $246 per acre, or roughly $24 per ton. Amortized costs are $216 per acre ($31/ton) and $229 per acre ($29/ton) on mid (WDFP) and low (MDSU) quality lands, respectively. The average cash rental rate in the six districts is $70 per acre. Under capacity procurement contract, $350/acre is not competitive on land of quality WDLU since, although it has the greatest yield, it also has the highest production cost per acre. The cost per ton, however, is lower on WDLU land so that a lower wholesale price is competitive on this quality of land since profit can be recouped via the volume produced. This suggests that the wholesale contract should be offered to farmers with more productive land, particularly if the expected price outlook for commodities is not very optimistic, as is the case for cotton and hay.

Tables 12 and 13 illustrate the price premium that must be offered in order to induce farmer participation in switchgrass production.[18] We compare the farmer's breakeven price for switchgrass (the price at which costs are recouped) with the minimum acceptable contract price, the price such that profit under contract to produce switchgrass is at least as great as profit without a contract. Keeping with the literature, breakeven prices are calculated as the sum of amortized establishment, production and land rent (opportunity) costs. To achieve units of cost per ton to facilitate comparisons under the wholesale contract structure we use the annualized

[18] Here we define a "premium" as the difference between the farmer's minimum acceptable contract price and the price at which all costs are recouped. It is the farmer's required markup.

Table 12: Comparison of breakeven price for feedstock production and minimum contract price required for wholesale contract acceptance by crop and land quality. (1) Double cropped soybeans and wheat.

| Crop | | Amortized Costs $/acre | Amortized Cash Rental Rate $/acre | Annualized Yield ton/acre·yr | Breakeven Price $/ton | Minimum Contract Price $/ton |
|---|---|---|---|---|---|---|
| Corn | | | | | | |
| | WDLU | 246 | 37 – 112 | 7.18 | 39 – 50 | 62 – 72 |
| | WDFP | 216 | 37 – 102 | 5.23 | 48 – 61 | 74 – 83 |
| | MDSU | 230 | 33 – 134 | 5.61 | 47 – 65 | 48 – 71 |
| Cotton | | | | | | |
| | WDLU | 246 | 100 – 106 | 7.18 | 48 – 49 | 53 – 56 |
| | WDFP | 216 | 40 – 110 | 5.23 | 49 – 62 | 60 – 67 |
| | MDSU | 230 | 65 – 112 | 5.61 | 53 – 61 | 53 – 61 |
| Soybeans | | | | | | |
| | WDLU | 246 | 37 – 71 | 7.18 | 39 – 44 | 56 – 70 |
| | WDFP | 216 | 41 –106 | 5.23 | 49 – 62 | 59 – 70 |
| | MDSU | 230 | 37 – 134 | 5.61 | 48 – 65 | 48 – 65 |
| Wheat | | | | | | |
| | MDSU | 230 | 36 – 90 | 5.61 | 47 – 57 | 47 – 57 |
| Double Crop(1) | WDLU | 246 | 47 – 67 | 7.18 | 41 – 44 | 52 – 68 |
| | WDFP | 216 | 46 – 106 | 5.23 | 50 – 62 | 61 – 75 |
| | MDSU | 230 | 36 – 134 | 5.61 | 47 – 65 | 48 – 84 |
| Hay | | | | | | |
| | WDLU | 246 | 32 – 82 | 7.18 | 39 – 46 | 51 – 54 |
| | WDFP | 216 | 34 – 100 | 5.23 | 48 – 60 | 63 – 65 |
| | MDSU | 230 | 33 – 134 | 5.61 | 47 – 65 | 56 – 65 |

Table 13: Comparison of breakeven price for feedstock production and minimum contract price required for capacity procurement contract acceptance by crop and land quality. (1) Double cropped soybeans and wheat.

| Crop | | Amortized Costs $/acre | Amortized Cash Rental Rate $/acre | Breakeven Price $/acre | Minimum Contract Price $/acre |
|---|---|---|---|---|---|
| Corn | | | | | |
| | WDLU | 246 | 37 – 112 | 284– 358 | 444 – 518 |
| | WDFP | 216 | 37 – 102 | 284 – 318 | 386 – 432 |
| | MDSU | 230 | 33 – 134 | 262 – 363 | 268 – 398 |
| Cotton | | | | | |
| | WDLU | 246 | 100 – 106 | 346 – 353 | 382 – 401 |
| | WDFP | 216 | 40 – 110 | 256 – 326 | 315 – 349 |
| | MDSU | 230 | 65 – 112 | 294 – 341 | 294 – 341 |
| Soybeans | | | | | |
| | WDLU | 246 | 37 – 71 | 284 – 317 | 405 – 506 |
| | WDFP | 216 | 41 –106 | 257 – 322 | 307 – 368 |
| | MDSU | 230 | 37 – 134 | 266 – 363 | 268 – 363 |
| Wheat | | | | | |
| | MDSU | 230 | 36 – 90 | 265 – 319 | 265 – 319 |
| Double | | | | | |
| Crop$^{(1)}$ | WDLU | 246 | 47 – 67 | 294 – 313 | 371 – 490 |
| | WDFP | 216 | 46 – 106 | 262 – 322 | 321 – 393 |
| | MDSU | 230 | 36 – 134 | 265 – 363 | 268 – 470 |
| Hay | | | | | |
| | WDLU | 246 | 32 – 82 | 278 – 328 | 368 – 385 |
| | WDFP | 216 | 34 – 100 | 250 – 316 | 329 – 338 |
| | MDSU | 230 | 33 – 134 | 262 – 363 | 312 – 363 |

switchgrass yield.

In general, price premiums are greatest on the most productive land—cropland of type WDLU—and for land used to grow soybeans and corn. For land growing corn, the minimum acceptable contract price is as much as 72% greater than the breakeven price on WDLU quality land, as much as 59% above breakeven on WDFP quality, and as much as 46% on MDSU. Similarly, for soybeans, the minimum acceptable contract price is as much as 78%, 40% and 17% on WDLU, WDFP and MDSU quality land, respectively.

For some crop-land quality pairs the breakeven price and minimum acceptable contract price coincide. This is true for counties in which commodity production is not profitable at expected future prices, due to low yields, so that in the absence of a contract the land would have been allocated toward the next best alternative, earning a return equal to the cash rental rate. This is the case for several counties growing cotton, soybeans and wheat on MDSU quality land.

To summarize the results we find that: 1) switchgrass production in the Tennessee case study is least competitive with corn and most competitive with wheat and hay; 2) the unit price (price per ton) of achieving a given maturity year switchgrass supply level is lower under the capacity procurement payment mechanism; 3) lower wholesale prices can be supported on high quality land due to the lower unit cost from higher yields, but low capacity procurement prices can only be supported on lower quality land where production costs are lower; and 4) unless expected future profit from commodity production is negative, breakeven pricing will not induce farmer participation in switchgrass production.

### 4.4.2 Sensitivity Analysis

In this section we evaluate the sensitivity of our results to key model parameters. We also evaluate the importance of yield and commercial scalability assumptions.

### Yield Variability

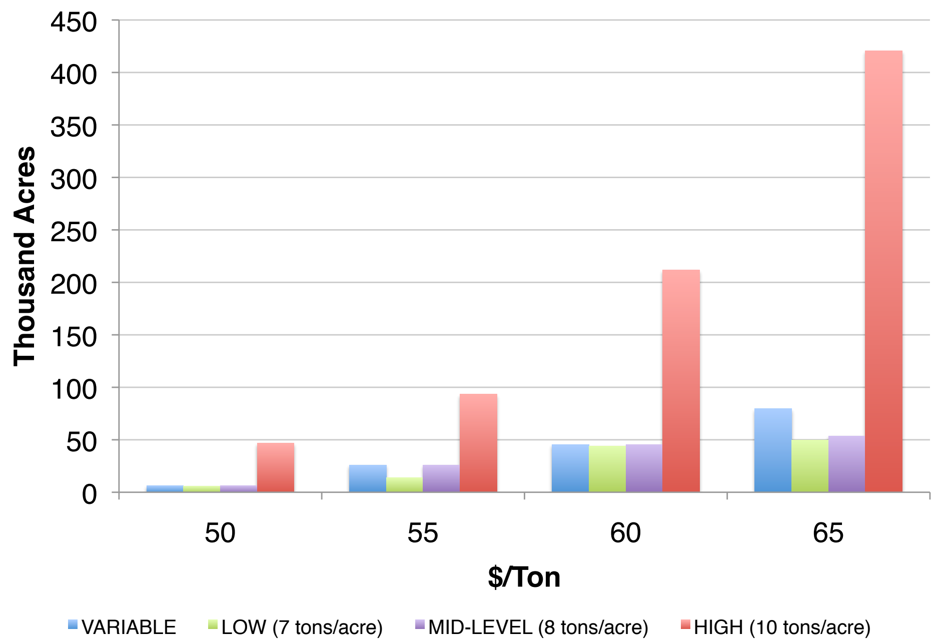



Figure 19: Displaced *corn* under wholesale contract when switchgrass yields do not vary with land quality. In the LOW case we assume the maximum switchgrass yield on all land is 7 tons per acre. The MID-LEVEL case assumes a yield of 8 tons per acre on all land; the HIGH case assumes 10 tons per acre is attainable on all land. The VARIABLE case depicts initial model results.

Recall that we classified the land productivity of each crop-county pair by its relative 2010 yield. To assess the importance of yield assumptions on supply estimates, and validate our land classification method, we compare corn displacement under varying land productivity assumptions for the wholesale contract structure, see Figure 19. From our initial results, in which switchgrass yields vary according to the productivity of the land on which it is grown, we concluded that switchgrass was least competitive with corn. We compare these initial competitiveness results with three different cases, LOW, MID-LEVEL, and HIGH, in which switchgrass yields do not vary according to the productivity of the land. But rather, all land, regardless of productivity classification (soil quality) produce the same expected switchgrass yield. The VARIABLE case denotes our initial results.

In the LOW case we assume switchgrass yield ($\beta_2^{ik}$) and production costs on all land qualities are 7 tons per acre and $216 per acre, respectively. This coincides with the yield and production costs on WDFP land. Similarly, yield and production costs in the MID-LEVEL case are, respectively, 8 tons per acre and $230 per acre, corresponding with the yield and costs on MDSU land. The HIGH case yields 10 tons per acre at a cost of $246 per acre, as with WDLU land. This sensitivity analysis compares corn displacement when a single switchgrass yield estimate is applied to the entire state (LOW, MID-LEVEL, or HIGH yield), versus displacement when switchgrass yield depends on land quality (VARIABLE).

Switchgrass competitiveness, hence potential supply, depends on the land quality classification in two ways: via the anticipated yield and the production cost. Considering the production cost (establishment, annual maintenance and harvest costs) to yield ratio, production is cheapest on WDLU land (HIGH scenario) at $34/ton, and most expensive on WDFP land (LOW scenario) at $41/ton; production on MDSU land (MID-LEVEL scenario) is also approximately $41/ton. When we include the cash rental rate (opportunity cost of land), per unit production costs range from $39 to $50 per ton on WDLU land, $48 to $61 per ton on WDFP land, and $47 to $65 per ton on MDSU land (see corn breakeven prices in Table 12).[19]

From Figure 19 it is evident that when yields on all land are HIGH switchgrass is most competitive with corn production. Since we assume all counties face the same cost of producing corn (based on the crop budget), regardless of its observed yield, those counties with low corn yields would find switchgrass production quite profitable

[19] Under capacity procurement contract, the farmer's payment is independent of the yield so any difference between the VARIABLE, LOW, MID-LEVEL, and HIGH cases would be a result of the change in production cost. We consider this later.

relative to corn production in this scenario. Precisely, at \$50/ton the average corn yield on the acres that converted to switchgrass was 37% lower than the average corn yield in the counties that did not elect to grow any switchgrass at that price. To the extent that low crop yields reflect low land productivity, a one-size-fits-all yield estimate could grossly overestimate potential supply availability if too optimistic.

At \$50/ton, \$55/ton, and \$60/ton, results from the MID-LEVEL case are identical to our initial VARIABLE case results. In the VARIABLE case, only lands of quality MDSU (where yields and costs are equivalent to those in the MID-LEVEL scenario) convert to switchgrass production at those prices, hence the equality. At \$60/ton, corn displacement under VARIABLE, LOW and MID-LEVEL scenarios are roughly equal. Of the 19 counties which convert land under the VARIABLE case at \$60/ton, all planted corn on land classified as MDSU. In the LOW case the same 19 counties convert land for switchgrass production and only one of those counties allocates fewer acres in the LOW scenario than it did in the VARIABLE case. However, at \$55/ton the difference in breakeven prices has a significant effect on displacement.

At \$55/ton the 16 counties which convert cropland under VARIABLE conditions are all of classification MDSU, again, explaining the equivalence between VARIABLE and MID-LEVEL results. In the LOW scenario, only 11 of those 16 counties convert cropland to switchgrass production. Of those 11, four convert fewer acres than under VARIABLE conditions. The reduction in conversion at \$55/ton under the LOW scenario is the result of an increase in each county's minimum acceptable contract price. For these counties, the difference in switchgrass production cost is not substantial (in both cases the production cost per ton is approximately \$41). However, the difference in opportunity cost, per ton, is considerable. In the LOW yield case, the opportunity cost of land in the 9 counties which converted fewer acres is \$0.50 to \$1.00 per ton greater than it is in the VARIABLE case where yields in those counties are assigned a higher value. Thus, counties with higher opportunity costs could not support the increase in total costs per ton under the LOW yield scenario.

This sensitivity analysis illustrates the importance of yield variability to biomass feedstock adoption. Applying high yield estimates to less productive cropland paints an overly optimistic view of feedstock competitiveness and, hence, farmer willingness to participate in biomass feedstock production. Similarly, low yield estimates understate the appeal of feedstock production on more productive land at competitive contract prices (e.g., $65/ton in Figure 19). Thus, with the research showing such variability in feedstock yield according to land productivity, this more refined approach to evaluating feedstock competitiveness and potential supply is warranted. This sensitivity analysis also suggests that improving yields on less productive land, especially in the years before switchgrass stands reach maturity, will be an important avenue through which a substantial supply of feedstock can be secured cheaply under wholesale contract.

### Wholesale versus Capacity Procurement Contract and the Yield Profile

The models discussed in Section 4.2 use annualized yields when estimating the competitiveness of switchgrass and anticipated supply. However, that approach ignores the importance of foregone revenues in early years that are important in the decision to adopt a perennial crop like switchgrass. The time it takes to establish the crop (approximately two years in the case of switchgrass) is especially important when the contract period is relatively short like the five year period we consider here. To understand the impact of prematurity yields (the fraction of maturity year yields that can be harvested in years one and two) on supply and crop displacement, we consider a scenario where the yield in each of the five years has been annualized to the maturity year yield. In other words, rather than incorporate the actual yield profile of the perennial crop, with fractional yields in early years and full maturity yields in

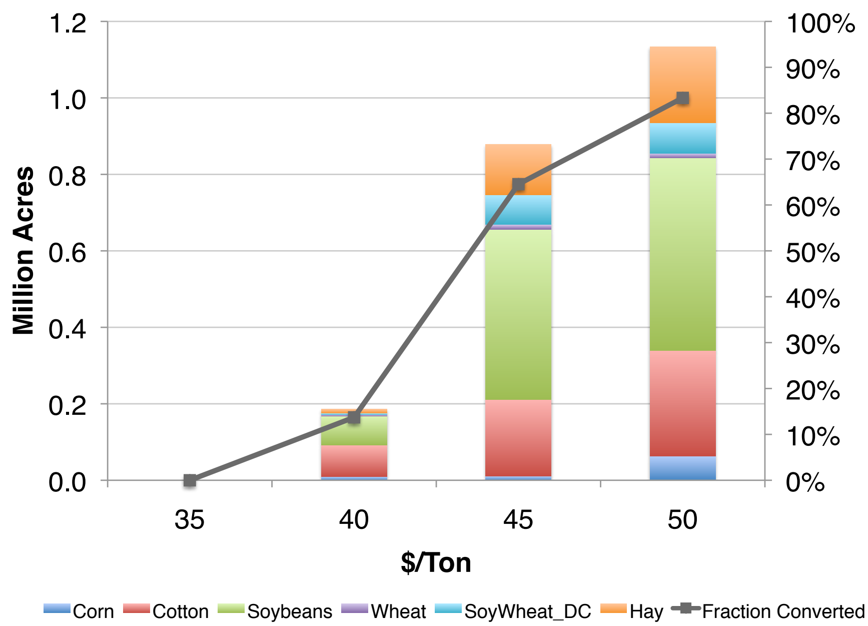



Figure 20: Converted cropland and displaced crops under wholesale contract when the decision to adopt switchgrass is made assuming annualized yields rather than the actual yield profile in which first and second year yields are only a fraction of maturity year yields. Columns indicate converted cropland (left vertical axis); square markers indicate the fraction of total District 20 cropland converted.

later years, we assume a constant yield for each period. Figure 20 illustrates potential supply in District 20 under this assumption.

Our initial results demonstrate that District 20 has the greatest potential for switchgrass production, due to its size, but only for prices at or above $65/ton. Assuming annualized yields, conversion is achieved at substantially lower prices, and switchgrass production is substantially more competitive with crops like corn even at such low prices (compare Figures 17(a) and 20).

Under wholesale contract the farmer is only paid per unit produced. So when yields are low for a substantial portion of the contract period, as in our model, only the promise of higher prices can induce farmer participation. However, when the decision to adopt is based on annualized yields, prices as low as $40/ton convert up to 14% of the district's cropland, while a price of $45/ton converts 65% of the district's cropland. When using the actual yield profile, Figure 17(a), no cropland is converted at prices below \$50/ton. The assumption of high yields in all years reduces the minimum acceptable contract price among counties in District 20 between 25% and 30%. This analysis suggests that for shorter time horizons, using annualized yields instead of actual yields will overstate the potential supply at any given price. It also suggests that, assuming comparable yield to cost ratios, wholesale contracts may be particularly successful at securing cheap biomass when the feedstock is an annual crop like sorghum. For more on sorghum as a potential dedicated bioenergy crop, see Rooney, et al. [96].

As a point of comparison, consider potential supply under capacity procurement contract—which is unaffected by the annualized yield assumption. 74% of District 20 cropland is allocated to switchgrass at \$350/acre. For a capacity procurement price of \$350/acre, the average price per ton at maturity is \$34, \$50, and \$44 on WDLU, WDFP, and MDSU lands, respectively. The overall average price per ton is \$45. Thus, with the annualized yield assumption, performance (land converted and price per ton switchgrass) under wholesale contract and capacity procurement contract is comparable. Since the annualized yield approach is reasonable over very long horizons, like those considered in the equilibrium models of Section 4.2, risk preferences would dictate which contract structure is best for long-term contracts. However, for shorter horizons, where annualized yields are not a reasonable assumption, capacity procurement contracts secure feedstock at a substantially higher cost to the biorefinery on a per unit basis.

When considering the actual yield profile of switchgrass, the average effective unit price of a \$350/acre capacity procurement price ranges from \$265/ton to \$353/ton in year one, based on land productivity[20], and between \$67/ton and \$88/ton in year two. Even when balanced with maturity year averages, which range from \$34/ton

[20] The average year one yield on MDSU land is less than one ton.

to \$50/ton, the average price per ton when offering a \$350/acre capacity procurement price ranges from \$87/ton to \$115/ton. On the other hand, the wholesale contract, Figure 17(a), induces 76% of district cropland at \$65/ton. Therefore, inducing roughly the same level of conversion—74% at \$350/acre, Figure 17(b)—costs on average 34% to 76% more per ton under capacity procurement contract. Thus, for shorter contract periods, when an annualized yield is not an appropriate assumption, the wholesale contract is the most cost effective method of securing biomass feedstock.

### Commercial Scalability

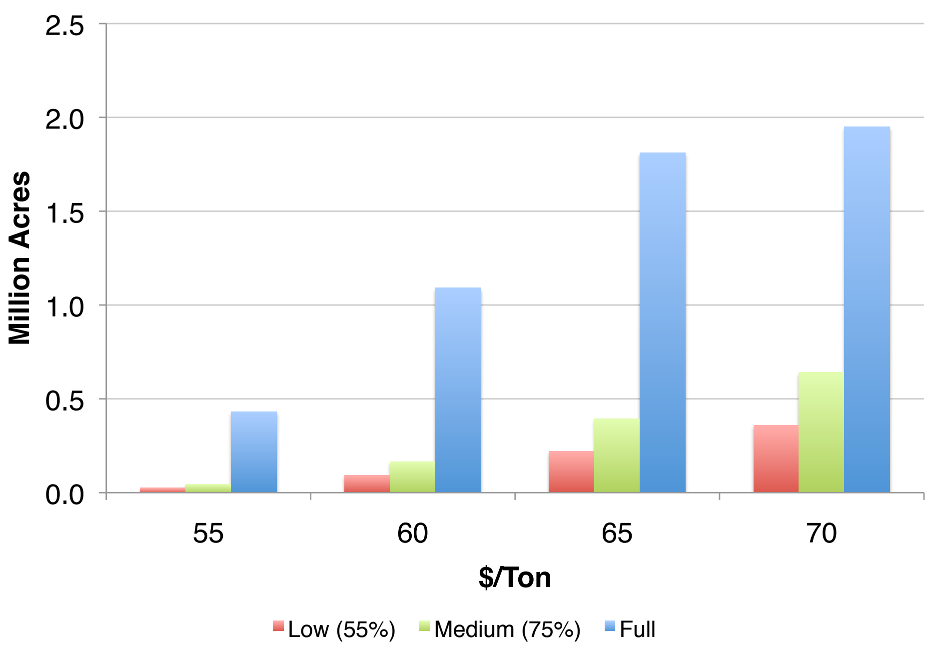



Figure 21: Displaced *hay* under wholesale contract assuming low, medium and full commercial scalability of feedstock production. Under low scalability, the average yield per acre is 55% of experimental yields at commercial scale production levels. At medium scalability, average yield per acre is 75% of the experimental yield at commercial scale production levels.

Whether experimental yields of cellulosic feedstocks can be sustained at higher production levels, which we refer to as "commercial scalability," is an important concern that very few studies consider. Since commercial scale cellulosic feedstock production does not yet exist, studies estimating potential supply must rely on the results of field trials and other simulation experiments, as we do in our model. However, it is not certain if the results seen will translate at the commercial scale. As noted previously, the potential for an increase in the severity of pest and disease outbreaks as the cultivation of cellulosic feedstocks intensifies is an important concern [85].

Our production function lends itself to a study of the consequences of the commercial scalability assumption. Recall (from Section 4.3.1.1) that switchgrass production is characterized by $f_2(L_2) = (\beta_2 - \delta_2 L_2)L_2$, where $\beta_2$ represents the maximum yield per unit area and $\delta_2$, the yield reduction rate, is the extent to which the yield per area decreases as total area increases. The results presented thus far have assumed full scalability, in line with the scalability of commodity crops. When all available acres are planted to switchgrass, the average yield per acre is between 98% and 99% of the maximum yield per unit area. Here we consider the impact of scalability on the supply and price of switchgrass by comparing our initial results of full commercial scalability with low and medium scalability assumptions. Under the low scalability assumption, when all available acres are planted to switchgrass the average yield per acre is 55% of the maximum; under medium scalability the average yield per acre is 75% of the maximum. In other words, we choose $\delta_2$ for each crop-county pair to solve:

$$\beta_2^{ik} - \delta_2^{ik} \check{L}^{ik} = \theta \beta_2^{ik}$$

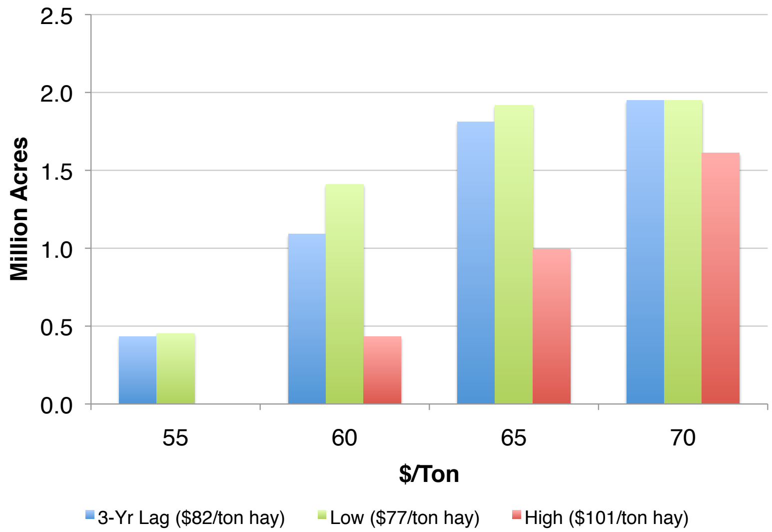
where $\theta = 0.55$ in the low scalability scenario and $\theta = 0.75$ in the medium scalability scenario. Figure 21 illustrates the results on cropland used to harvest hay.

Under wholesale contract, crop displacement is remarkably sensitive to the assumption of full commercial scalability. At \$55/ton, hay acreage converted under low and medium scalability is only 5.9% and 10.5% of full scalability conversion, respectively. At $70/ton, acreage conversion is only 18.4% and 32.8% of full scalability conversion for the low and medium cases, respectively. Poor scalability increases the farm gate price required to secure feedstock and will increase total costs as the requisite feedstock supply would have to be obtained in smaller batches from more farms. This suggests the importance of research which develops best practices for managing feedstock production at a larger scale.

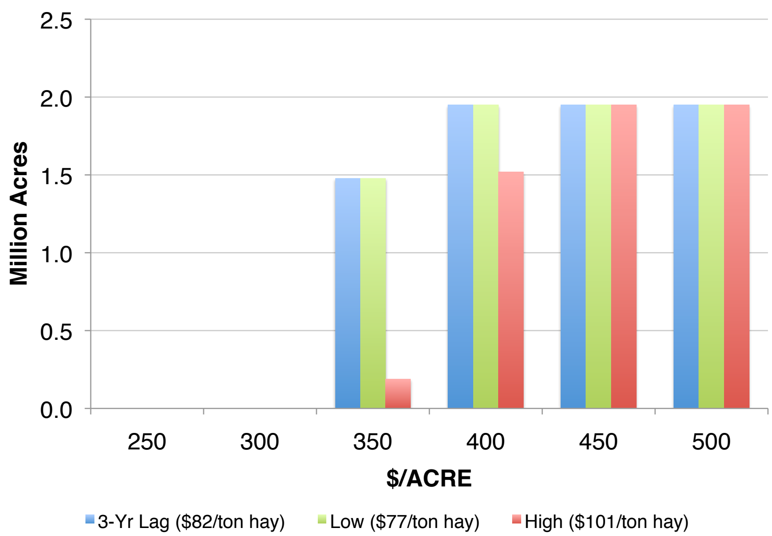
**Expected Spot Price**

As expected, the conversion of cropland to switchgrass production is quite sensitive to the expected commodity price. Figure 22 illustrates switchgrass competitiveness with hay under varying commodity price expectations. In our initial results, cropland harvesting hay is converted in substantial quantities. We vary the 3-year lag price to see how sensitive conversion is to expected future commodity prices.

Under wholesale contract, Figure 22(a), when the future price is expected to be high ($101 per ton hay) no land is converted at $55 per ton and only 22% of the cropland harvesting hay could be converted at $60 per ton. This compares with our initial result of 56% conversion at $60/ton. Similarly, at a wholesale price of $65/ton switchgrass is competitive on roughly 51% of cropland harvesting hay, compared with our initial result of 93% conversion. When the price outlook for hay is low ($77 per ton), $55/ton does not induce much conversion over that suggested by our initial results since the opportunity cost (cash rental rate) drives competition with switchgrass production in that instance. At $65/ton all of the hay in the state is displaced when the price outlook is low. Under capacity procurement contract, Figure 22(b), the increased value of hay is most pronounced for a contract price of $350/acre. In our initial results $350/acre is sufficient to compete with 76% of hay acres; when the price




(a) Wholesale Contract




(b) Capacity Procurement Contract

Figure 22: Displaced *hay* under (a) wholesale and (b) capacity procurement contracts at various commodity price expectations. The 3-Yr Lag case represents initial model results; the low case illustrates hay displacement using recent (2009–2010) hay prices received by Tennessee farmers as the expected outlook; the high case illustrates displacement using the average price of hay in 2008 as the expected price outlook.

outlook is particularly optimistic ($101 per ton), that price competes with less than 10% of cropland harvesting hay. In 2008 the average price per ton of hay received by Tennessee farmers was $101 per ton. In 2009 and 2010 the average price received was $78/ton and $75/ton, respectively. In the absence of a central market for the sale of hay, a farmer's belief about its future value has a very important effect on the potential adoption of biomass feedstocks.

### Feedstock Production Cost

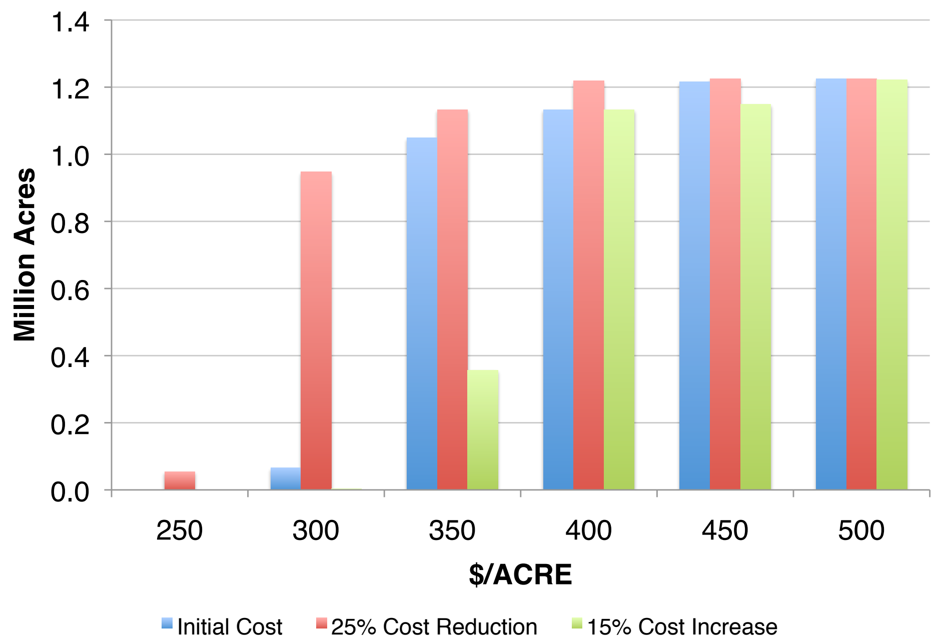



Figure 23: Displaced *soybean* under capacity procurement contract by annual switchgrass production cost. The Initial Cost case illustrates our initial model results. The Cost Reduction case illustrates soybean displacement when annual production costs are 25% less than the Initial Cost. The Cost Increase case illustrates displacement when annual production costs are 15% greater than the Initial Cost.

Figure 23 illustrates switchgrass competitiveness with soybean acres under varying switchgrass production cost for several cases. Keeping establishment costs the same as in our initial model run, we investigate the impact of increasing the annual production and harvest (maintenance) costs by 15%, as well as that of reducing them by 25%. Nitrogen fertilization, an important factor in annual maintenance costs, has been the topic of many switchgrass production trials (see [83] and the references therein). The figure illustrates a 25% reduction in production costs has a big impact on competitiveness at lower capacity procurement prices. A capacity procurement price of $250/acre is competitive with nearly 55,000 soybean acres when costs are reduced. Interestingly, the cost increase is negligible, relative to our initial competitiveness results, except at $350 per acre where conversion potential is 6% of that determined initially.

## *4.5 Conclusions*

In this chapter we have put forth a method for estimating potential feedstock supply and its resultant impact on the agricultural landscape that focuses on a farmer's land allocation decision between competing endeavors under two different payment schemes. Our nonlinear approach to the land allocation problem allows us to evaluate key components in the decision to adopt a new bioenergy crop that linear decision models cannot address, namely, the importance of commercial scalability in production. By incorporating the results of field trials which suggest switchgrass production is sensitive to soil and land characteristics, we demonstrate the importance of yield variability on price and potential feedstock availability. Our approach also highlights the importance of a perennial crop's yield profile on the decision to adopt when a pay per ton contract is offered as opposed to a contract which pays per area of land.

While this work contributes to the body of literature on the agricultural impacts of cellulosic biofuel production, it does have several limitations. Like most other studies, our analysis only illustrates switchgrass potential by considering farm gate prices. The cost of transporting feedstock is a very important factor in this system. We have not considered transportation costs explicitly because they rely on many factors that are hard to estimate. However, based on the estimates put forth in the literature and the demonstration plant's willingness to pay, switchgrass production in Tennessee seems viable.

This analysis focused on the competitiveness of switchgrass production on active cropland. We did not consider lands that have been idled or land used for pasture, largely in order to maintain the consistency of our data sources, but also because switchgrass yields are highest on cropland and this type of production is most controversial due to the inherent competition with food crops. Securing an adequate supply of feedstock for commercial scale cellulosic biofuel production will require the use of substantial cropland. The analysis presented here shows that Tennessee could support at least one large biorefinery at a reasonable price without drastically altering the agricultural landscape, particularly as it relates to food crops. However, this analysis does not consider any potential feedback effects from the crop displacement. The livestock sector is important in Tennessee and our model predicts that a substantial amount of cropland used to harvest hay would be converted to switchgrass production. Thus, the impacts of conversion in Tennessee might be felt largely by livestock producers, especially when drought and other conditions affect pasture lands.

Though this modeling effort is deterministic, we do provide sensitivity analysis in order to test the robustness of our results to key modeling parameters. Lacking a reasonable basis from which probability distributions could be developed, a stochastic model would add little value.

Despite its limitations, this effort makes important contributions with respect to some of the near-term challenges facing next-generation biofuel production. Though we focused on switchgrass production in Tennessee, the model can be easily adapted to other cellulosic feedstocks in other locations once the appropriate data are obtained. In providing estimates of the economic potential for switchgrass production at the county level, model results can be used to make more informed decisions about where to site biorefineries. And in providing estimates under two payment mechanisms, biorefineries can assess the contract structure that is most appropriate for the farmer's circumstances.

## *4.6 Appendix*

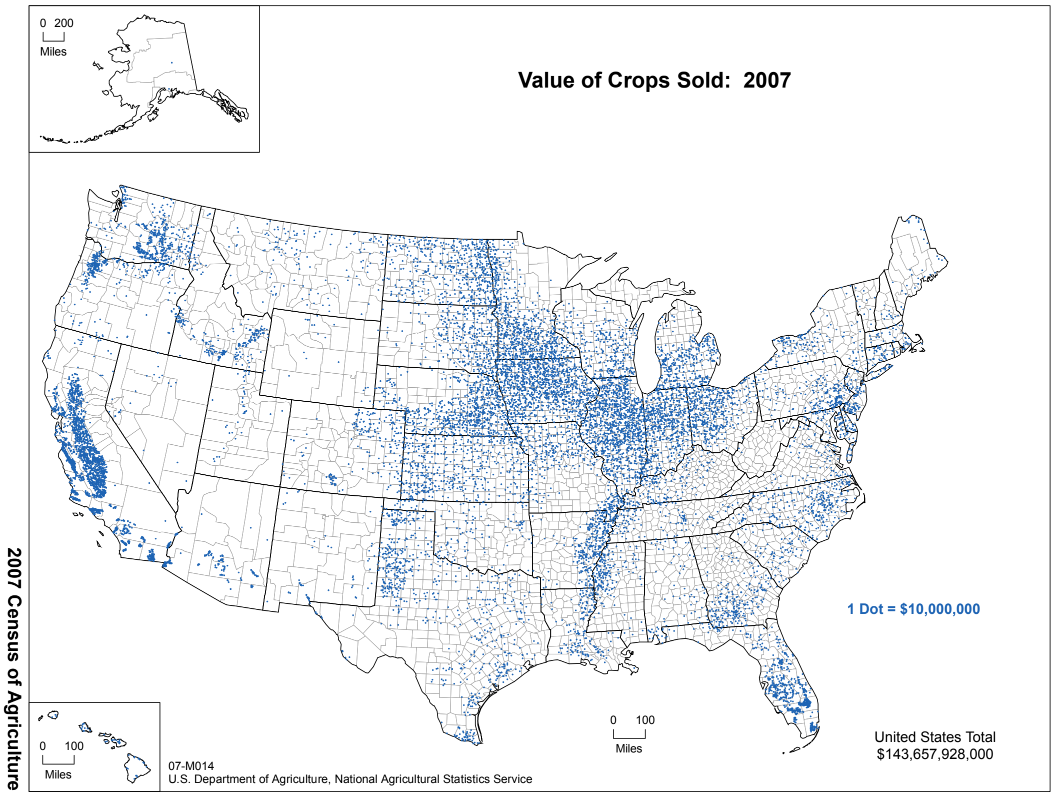



Figure 24: Geospatial map of the value of crops sold in the United States in 2007. Source: U.S. Department of Agriculture, National Agricultural Statistics Service. 2007 Census of Agriculture.

### 4.6.1 Counties in Tennessee by Value of Crops Sold (2007) and Agricultural Statistics Districts

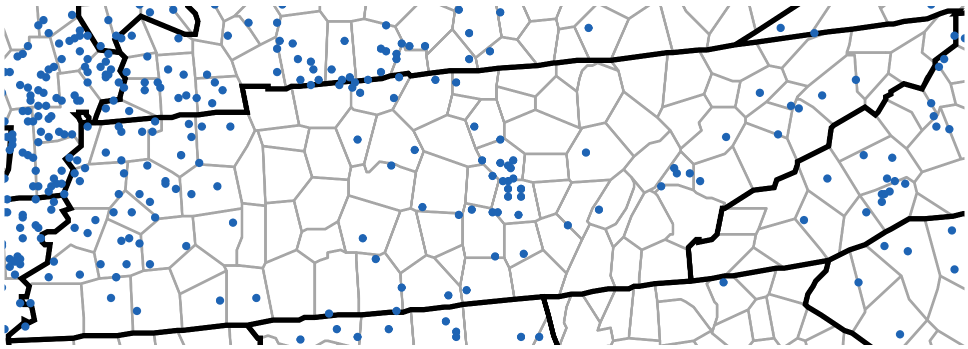


Figure 25: Value of crops sold in Tennessee in 2007. Zoomed in from national map (Figure 24).

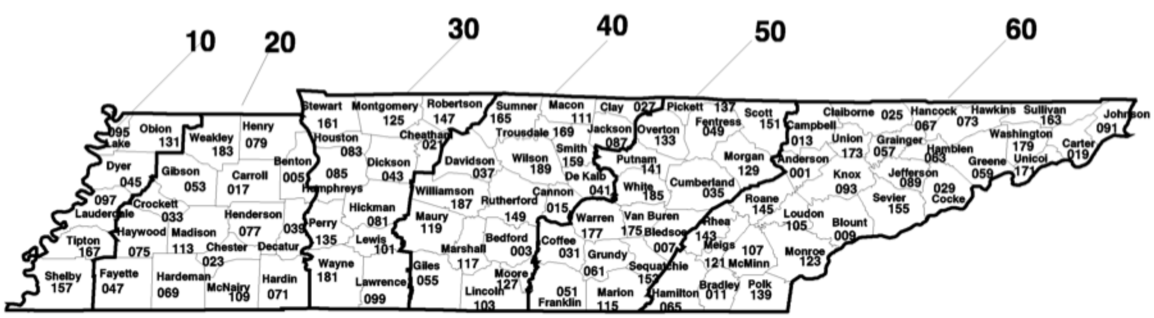
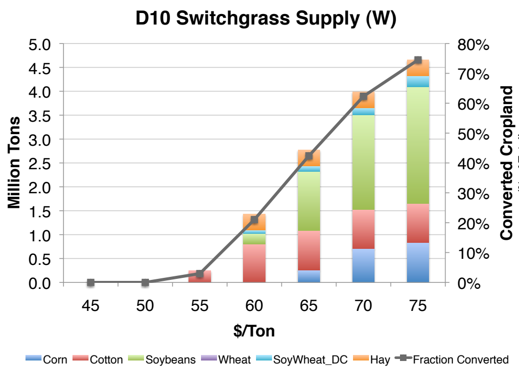
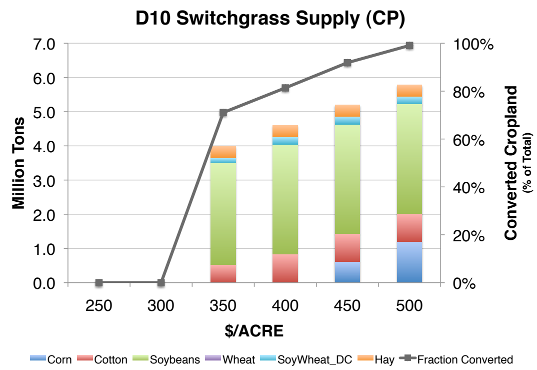



Figure 26: Agricultural Statistics Districts in Tennessee

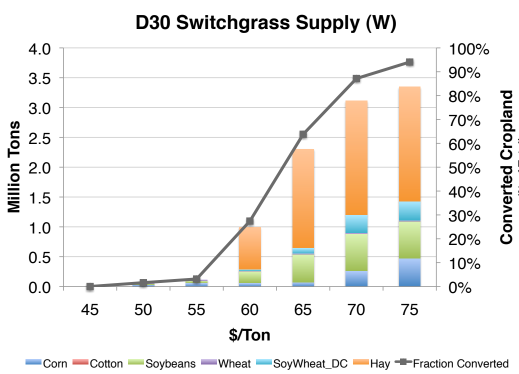
### 4.6.2 Crop Displacement and Switchgrass Production by District and Contract Type



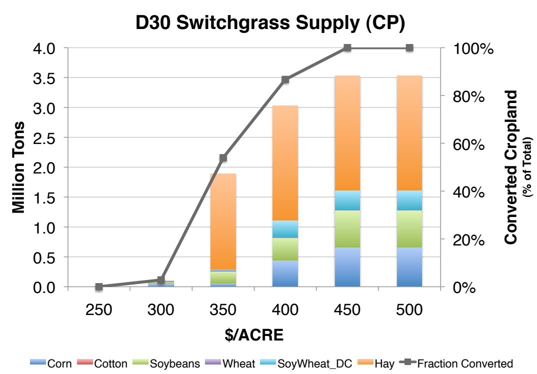

(a) Wholesale Contract




(b) Capacity Procurement Contract

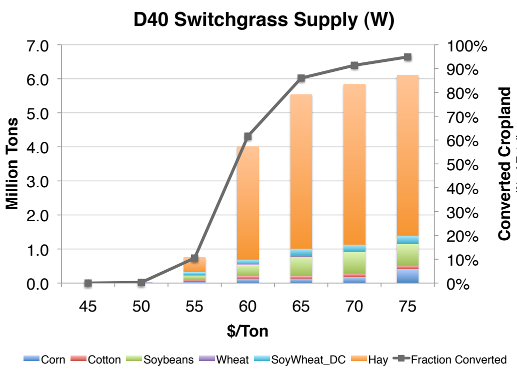



(c) Wholesale Contract

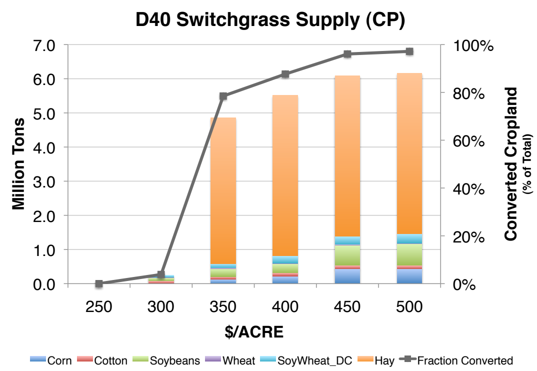



(d) Capacity Procurement Contract

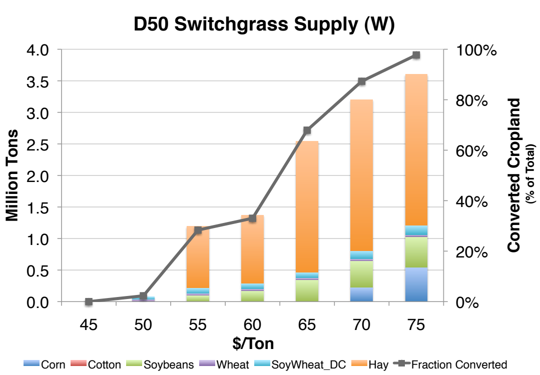
Figure 27: Crops Displaced in Districts 10 and 30



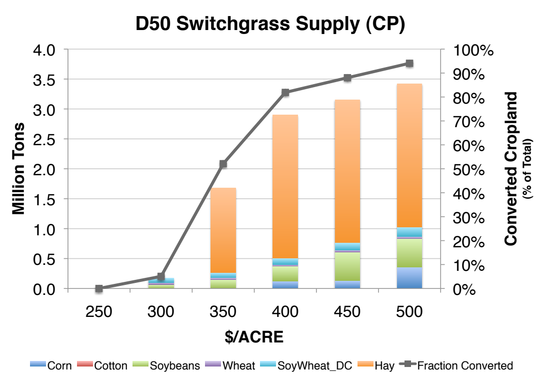

(a) Wholesale Contract




(b) Capacity Procurement Contract




(c) Wholesale Contract




(d) Capacity Procurement Contract

Figure 28: Crops Displaced in Districts 40 and 50

# CHAPTER V

# CONCLUSION

Borne out of an interest in the food-versus-fuel debate as it pertains to next-generation biofuel production, this dissertation uses microeconomic and supply chain coordination principles to model the interaction between an agricultural producer and biorefinery who enter into a contractual arrangement for the supply and procurement of biomass feedstocks. Our model focuses on a farmer's decision to use productive cropland for biomass versus commodity (food) crops and how a biorefinery can use contract terms to influence that decision. In so doing we have provided a framework for understanding the potential effects non-food energy crops can have on food production through indirect competition for scarce land resources.

Agricultural contracting for production (e.g., crops, livestock) is becoming increasingly prevalent in U.S. agriculture (in 2005, production under contract accounted for 41% of the value of U.S. agricultural production, up from 36% in 2001 and 28% in 1991). And in the developing world where agriculture is often the most important economic sector, many countries (particularly in Africa) are looking toward contract farming as a way to encourage production and farmer access to markets. There has not, however, been much study of the design of agricultural contracts, especially from a supply chain perspective.

By comparing several contract structures according to their ability to achieve target participation goals, improve total system performance and distribute profits between agents, this study provides a framework for evaluating contract design in an agricultural context, providing useful insights into the factors with the most substantial influence over equilibrium outcomes. In evaluating equilibrium outcomes across types of farmers who enter into contracts for very distinct reasons, we have identified the effects of implicit and explicit competition from non-contracted production on contract terms and contract acceptance. And with respect to near term feasibility of next-generation biofuel production we have demonstrated the importance of yield variability, commercial scalability, and payment structure in estimating the potential supply of biomass and in assessing the impact of energy crop production on the agricultural landscape via the commodity (food) crops they displace. By assessing the economic potential of energy crop production at the county level, the results of our model can be used to make more informed decisions about where to site biorefineries. And, by analyzing economic potential under two different payment mechanisms, we have identified key features that will help biorefineries and agricultural producers arrive at the contract structure most appropriate for their circumstances and needs.

The challenge of securing an adequate supply of feedstock is just one of several roadblocks impeding large scale production of next-generation biofuels. This challenge is an important one, however, due to potential ramifications on the food system. Understanding the impact of energy crop production on agricultural land use is one step toward identifying potential consequences on the food system. Another important step—particularly as it relates to establishing an industry for next-generation biofuels in the near term—may include modeling and evaluating the economic feasibility and food system impacts of regionally concentrated bioenergy production.

# REFERENCES


[1] "PB1638 Marketing Hay in Tennessee." The University of Tennessee Agricultural Extension Service, PB1638-1M-11/99 E12-2015-00-113-00, http://trace.tennessee.edu/utk_agexfora/1.

[2] "The University of Tennessee–DuPont Danisco Cellulosic Ethanol (DDCE) collaboration: Frequently asked questions." www.tennessee.edu/media/kits/biorefinery/docs/faq.pdf, Accessed: January 23, 2012.

[3] Agrawal, P., "Contractual structure in agriculture," *Journal of Economic Behavior & Organization*, vol. 39, no. 3, pp. 293 – 325, 1999.

[4] Ahumada, O. and Villalobos, J. R., "Application of planning models in the agri-food supply chain: A review," *European Journal of Operational Research*, vol. 196, no. 1, pp. 1 – 20, 2009.

[5] Ajanovic, A., "Biofuels versus food production: Does biofuels production increase food prices?," *Energy*, vol. 36, no. 4, pp. 2070–2076, 2011.

[6] Alexander, C., Ivanic, R., Rosch, S., Tyner, W., Wu, S. Y., and Yoder, J. R., "Contract theory and implications for perennial energy crop contracting," *Energy Economics*, 2011. In Press, Corrected Proof.

[7] Anupindi, R. and Akella, R., "An inventory model with commitments," *Unpublished manuscript, Northwestern University*, 1993. October.

[8] Anupindi, R. and Bassok, Y., "Supply contracts with quantity commitments and stochastic demand," in *Quantitative models for supply chain management*, pp. 197–232, 1999.

[9] Barnes-Schuster, D., Bassok, Y., and Anupindi, R., "Coordination and flexibility in supply contracts with options.," *Manufacturing & Service Operations Management*, vol. 4, no. 3, p. 171, 2002.

[10] Bassok, Y. and Anupindi, R., "Analysis of supply contracts with total minimum commitment," *IIE Transactions*, vol. 29, pp. 373–381, 1997.

[11] Bassok, Y. and Anupindi, R., "Analysis of supply contracts with commitments and flexibility," *Naval Research Logistics (NRL)*, vol. 55, no. 5, pp. 459–477, 2008.

[12] Bazen, E. F., Roberts, R. K., Travis, J., and Larson, J. A., "Factors affecting hay supply and demand in Tennessee," Annual Meeting, February 2-6, 2008, Dallas, Texas, Southern Agricultural Economics Association, 2008.

[13] Beach, R. H. and McCarl, B. A., "U.S. agricultural and forestry impacts of the Energy Independence and Security Act: FASOM results and model description," tech. rep., 2010.

[14] Birur, D., Hertel, T., and Tyner, W., "Impact of biofuel production on world agricultural markets: A computable general equilibrium analysis," *GTAP Working Papers*, 2008.

[15] Bolton, P. and Dewatripont, M., *Contract theory*. The MIT Press, 2005.

[16] Boyabatli, O., Kleindorfer, P. R., and Koontz, S. R., "Integrating long-term and short-term contracting in beef supply chains," *Management Science*, vol. 57, no. 10, pp. 1771–1787, October 2011.

[17] Bureau of Labor Statistics, "Consumer price index," 2011. http://www.bls.gov/cpi/.

[18] Burer, S., Jones, P. C., and Lowe, T. J., "Coordinating the supply chain in the agricultural seed industry," *European Journal of Operational Research*, vol. 185, no. 1, pp. 354 – 377, 2008.

[19] Cachon, G. P., "Supply chain coordination with contracts," in *Handbooks in operations research and management science* (de Kok, A. G. and Graves, S. C., eds.), vol. 11, pp. 229–340, Amsterdam, The Netherlands: Elsevier, 2003.

[20] Cachon, G. P. and Lariviere, M. A., "Capacity allocation using past sales: When to turn-and-earn," *Management Science*, vol. 45, no. 5, pp. 685–703, 1999.

[21] Cachon, G. P. and Lariviere, M. A., "Capacity choice and allocation: strategic behavior and supply chain performance," *Management Science*, pp. 1091–1108, 1999.

[22] Cachon, G. P. and Lariviere, M. A., "Contracting to assure supply: How to share demand forecasts in a supply chain," *Management Science*, vol. 47, no. 5, pp. 629–646, 2001.

[23] Carriquiry, M. A. and Babcock, B. A., "Can spot and contract markets co-exist in agriculture?," *Center for Agricultural and Rural Development (CARD)*, 2002. Working Paper 02-WP 311.

[24] Chen, X., Huang, H., Khanna, M., and Onal, H., "Meeting the Mandate for Biofuels: Implications for Land Use, Food and Fuel Prices," *SSRN eLibrary*, 2010.

[25] Choi, S. C., "Price competition in a channel structure with a common retailer," *Marketing Science*, vol. 10, no. 4, pp. pp. 271–296, 1991.

[26] Coyle, W. T., "Next-generation biofuels: Near-term challenges and implications for agriculture," *U.S. Department of Agriculture, Economic Research Service*, 2010. Outlook Report No. BIO-01-01.

[27] de Koff, J. P. and Tyler, D. D., "Improving switchgrass yields for bioenergy production," *UT Extension Publications*, 2011. W271.

[28] De La Torre Ugarte, D. G. and Ray, D. E., "Biomass and bioenergy applications of the POLYSYS modeling framework," *Biomass and Bioenergy*, vol. 18, no. 4, pp. 291–308, 2000.

[29] De La Torre Ugarte, D. G., English, B. C., and Jensen, K., "Sixty billion gallons by 2030: Economic and agricultural impacts of ethanol and biodiesel expansion.," *American Journal of Agricultural Economics*, vol. 89, no. 5, pp. 1290 – 1295, 2007.

[30] DeCroix, G. A. and Arreola-Risa, A., "Optimal production and inventory policy for multiple products under resource constraints," *Management Science*, vol. 44, no. 7, pp. pp. 950–961, 1998.

[31] Dicks, M. R., Campiche, J., De La Torre Ugarte, D. G., Hellwinckel, C., Bryant, H. L., and Richardson, J. W., "Land use implications of expanding biofuel demand," *Journal of Agricultural and Applied Economics*, vol. 41, no. 2, pp. 435–453, 2009.

[32] Downing, M., Eaton, L. M., Graham, R. L., Langholtz, M. H., Perlack, R. D., Turhollow Jr, A. F., Stokes, B., and Brandt, C. C., "U.S. billion-ton update: Biomass supply for a bioenergy and bioproducts industry," tech. rep., Oak Ridge National Laboratory (ORNL), 2011.

[33] Downing, M. and Graham, R. L., "The potential supply and cost of biomass from energy crops in the Tennessee valley authority region," *Biomass and Bioenergy*, vol. 11, no. 4, pp. 283 – 303, 1996.

[34] EIA, Energy Information Administration, "Fuel ethanol overview, 1981-2009," *Annual Energy Review (AER) 2009*. Table 10.3, DOE/EIA-0384(2009).

[35] Epplin, F. M., Clark, C. D., Roberts, R. K., and Hwang, S., "Challenges to the development of a dedicated energy crop," *American Journal of Agricultural Economics*, vol. 89, pp. 1296–1302, 2007.

[36] Erhun, F., Keskinocak, P., and Tayur, S., "Dynamic procurement in a capacitated supply chain facing uncertain demand," *IIE Transactions*, vol. 40, no. 8, pp. 733–748, 2008.

[37] Erkoc, M. and Wu, S. D., "Managing high-tech capacity expansion via reservation contracts," *Production & Operations Management*, vol. 14, no. 2, pp. 232–251, 2005.

[38] Ertek, G. and Griffin, P. M., "Supplier- and buyer-driven channels in a two-stage supply chain," *IIE Transactions*, vol. 34, pp. 691–700, 2002.

[39] Eswaran, M. and Kotwal, A., "A theory of contractual structure in agriculture," *American Economic Review*, vol. 75, no. 3, p. 352, 1985.

[40] Evans, R. V., "Inventory control of a multiproduct system with a limited production resource," *Naval Research Logistics Quarterly*, vol. 14, no. 2, pp. 173–184, 1967.

[41] Fabiosa, J. F., Beghin, J. C., Fengxia, D., Elobeid, A., Tokgoz, S., and Tun-Hsiang, Y., "Land allocation effects of the global ethanol surge: Predictions from the international FAPRI model.," *Land Economics*, vol. 86, no. 4, pp. 687 – 706, 2010.

[42] FAPRI, "Food and Agricultural Policy Research Institute." http://www.fapri.org/, Accessed: January 20, 2012.

[43] FAPRI, "Food and Agricultural Policy Research Institute: International ethanol model." http://www.fapri.iastate.edu/models/ethanol.aspx, Accessed: January 20, 2012.

[44] Fargione, J., Hill, J., Tilman, D., Polasky, S., and Hawthorne, P., "Land clearing and the biofuel carbon debt," *Science*, vol. 319, no. 5867, pp. 1235–1238, 2008.

[45] Farrell, A. E., Plevin, R. J., Turner, B. T., Jones, A. D., O'Hare, M., and Kammen, D. M., "Ethanol can contribute to energy and environmental goals," *Science*, vol. 311, no. 5760, pp. 506–508, 2006.

[46] Ferguson, M. E., "When to commit in a serial supply chain with forecast updating," *Naval Research Logistics (NRL)*, vol. 50, no. 8, pp. 917–936, 2003.

[47] Fine, C. H. and Freund, R. M., "Optimal investment in product-flexible manufacturing capacity," *Management Science*, vol. 36, no. 4, pp. pp. 449–466, 1990.

[48] Gerber, N., Van Eckert, M., and Breuer, T., "The impacts of biofuel production on food prices: A review," *SSRN eLibrary*, 2009.

[49] Gerchak, Y. and Wang, Y., "Revenue-sharing vs. wholesale-price contracts in assembly systems with random demand.," *Production & Operations Management*, vol. 13, no. 1, pp. 23 – 33, 2004.

[50] Glasserman, P., “Allocating production capacity among multiple products,” *Operations Research*, vol. 44, no. 5, pp. pp. 724–734, 1996.

[51] Global Trade Analysis Project (GTAP), “GTAP research: Energy.” https://www.gtap.agecon.purdue.edu/models/energy/default.asp.

[52] Global Trade Analysis Project (GTAP), “GTAP working paper series.” https://www.gtap.agecon.purdue.edu/resources/working_papers.asp.

[53] Goldman, D., “Food price spike: is ethanol to blame?,” *CNN Money.com*, 2008.

[54] Graham, R. L., English, B. C., and Noon, C. E., “A Geographic Information System-based modeling system for evaluating the cost of delivered energy crop feedstock,” *Biomass and Bioenergy*, vol. 18, no. 4, pp. 309–329, 2000.

[55] Hart, O. and Holmstrom, B., *The theory of contracts*. Cambridge, Massachusetts: Department of Economics, Massachusetts Institute of Technology, 1986.

[56] Hayes, D., Babcock, B., Fabiosa, J., Tokgoz, S., Elobeid, A., Yu, T.-H., Dong, F., Hart, C., Chavez, E., Pan, S., Carriquiry, M., and Dumortier, J., “Biofuels: Potential production capacity, effects on grain and livestock sectors, and implications for food prices and consumers,” *Journal of Agricultural and Applied Economics*, vol. 41, no. 2, pp. 465–491, 2009.

[57] Holin, F., “A market for switchgrass: State’s field–to–factory biofuel effort begins,” *Hay & Forage Grower*, January 1, 2010. http://hayandforage.com/marketing/archive/0101-switchgrass-biofuel-market, Accessed: January 23, 2012.

[58] Howitt, R. E., “Positive mathematical programming,” *American Journal of Agricultural Economics*, vol. 77, no. 2, pp. 329–342, 1995.

[59] IPM, “Crop profile for wheat production in Tennessee,” tech. rep., Regional Integrated Pest Management Centers (IPM), USDA, 2007. www.ipmcenters.org/cropprofiles/docs/TNwheat.pdf.

[60] Jensen, K., Clark, C. D., Ellis, P., English, B., Menard, J., Walsh, M., and De La Torre Ugarte, D. G., “Farmer willingness to grow switchgrass for energy production,” *Biomass and Bioenergy*, vol. 31, no. 11-12, pp. 773–781, 2007.

[61] Kazaz, B., “Production planning under yield and demand uncertainty with yield-dependent cost and price,” *Manufacturing & Service Operations Management*, vol. 6, no. 3, pp. 209 – 224, 2004.

[62] Kazaz, B. and Webster, S., "The impact of yield-dependent trading costs on pricing and production planning under supply uncertainty," *Manufacturing & Service Operations Management*, vol. 13, no. 3, pp. 404–417, Summer 2011.

[63] Keil, A., "Farmers growing switchgrass for planned Vonore ethanol facility," 2008. http://www.wate.com/global/story.asp?s=8726297. Accessed January 13, 2012.

[64] Khanna, M., Chen, X., Huang, H., and Onal, H., "Supply of cellulosic biofuel feedstocks and regional production pattern," *American Journal of Agricultural Economics*, vol. 93, no. 2, pp. 473–480, 2011.

[65] Kretschmer, B. and Peterson, S., "Integrating bioenergy into computable general equilibrium models—a survey," *Energy Economics*, vol. 32, no. 3, pp. 673 – 686, 2010.

[66] Laffont, J. J. and Martimort, D., *The theory of incentives: the principal-agent model*. Princeton University Press, 2002.

[67] Lariviere, M. A., "Supply chain contracting and coordination with stochastic demand," in *Quantitative Models for Supply Chain Management* (Tayur, S., Ganeshan, R., and Magazine, M., eds.), vol. 17, pp. 233–268, Kluwer Academic Publishers, 1999.

[68] Larson, J. A., English, B. C., and Lambert, L., "Economic analysis of the conditions for which farmers will supply biomass feedstocks for energy production," 2007.

[69] Lau, A. H. L., Lau, H.-S., and Wang, J.-C., "How a dominant retailer might design a purchase contract for a newsvendor-type product with price-sensitive demand," *European Journal of Operational Research*, vol. 190, no. 2, pp. 443–458, 2008.

[70] Liska, A. J., Yang, H. S., Bremer, V. R., Klopfenstein, T. J., Walters, D. T., Erickson, G. E., and Cassman, K. G., "Improvements in life cycle energy efficiency and greenhouse gas emissions of corn ethanol," *Journal of Industrial Ecology*, vol. 13, no. 1, pp. 58–74, 2009.

[71] Liu, X. and Cetinkaya, S., "Designing supply contracts in supplier vs buyer-driven channels: The impact of leadership, contract flexibility and information asymmetry," *IIE Transactions*, vol. 41, no. 8, pp. 687–701, 2009.

[72] Lowe, T. J. and Preckel, P. V., "Decision technologies for agribusiness problems: A brief review of selected literature and a call for research.," *Manufacturing & Service Operations Management*, vol. 6, no. 3, pp. 201 – 208, 2004.

[73] Lubowski, R. N., Plantinga, A. J., and Stavins, R. N., "What drives land-use change in the United States? a national analysis of landowner decisions," *Land Economics*, vol. 84, no. 4, pp. 529–550, 2008.

[74] Lynne, G. D., "Allocatable fixed inputs and jointness in agricultural production: implications for economic modeling: comment," *American Journal of Agricultural Economics*, vol. 70, no. 4, pp. 947–949, 1988.

[75] MacDonald, J. M., Perry, J., Ahearn, M. C., Banker, D., Chambers, W., Dimitri, C., Key, N., Nelson, K. E., and Southard, L. W., "Contracts, markets, and prices: Organizing the production and use of agricultural commodities," 2004.

[76] MacDonald, J. M. and Korb, P., "Agricultural contracting update: Contracts in 2008," 2011.

[77] Mas-Colell, A., Whinston, M. D., and Green, J. R., *Microeconomic theory*. New York: Oxford University Press, 1995.

[78] Mazzola, J. B. and Schantz, R. H., "Single-facility resource allocation under capacity-based economies and diseconomies of scope," *Management Science*, vol. 41, no. 4, pp. 669–689, 1995.

[79] McKinley, T. L., Gerloff, D. C., and The University of Tennessee, "Field crop budgets for 2011," tech. rep., 2011.

[80] McLaughlin, S. B. and Adams Kszos, L., "Development of switchgrass (Panicum virgatum) as a bioenergy feedstock in the United States," *Biomass and Bioenergy*, vol. 28, no. 6, pp. 515–535, 2005.

[81] Mitchell, D., "A note on rising food prices," *World Bank Development Prospects Group*, 2008. Policy Research Working Paper 4682.

[82] Mitchell, R., Vogel, K., and Sarath, G., "Managing and enhancing switchgrass as a bioenergy feedstock," *Biofuels, Bioproducts, & Biorefining (Biofpr)*, vol. 2, pp. 530–539, 2008.

[83] Mooney, D. F., Roberts, R. K., English, B. C., Tyler, D. D., and Larson, J. A., "Yield and breakeven price of 'Alamo' switchgrass for biofuels in Tennessee," *Agronomy Journal*, vol. 101, no. 5, pp. 1234–1242, 2009.

[84] Moschini, G., "Normal inputs and joint production with allocatable fixed factors," *American Journal of Agricultural Economics*, vol. 71, no. 4, pp. 1021–1024, 1989.

[85] National Research Council, *Renewable Fuel Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy*. Washington, DC: The National Academies Press, 2011.

[86] Parker, N., Tittmann, P., Hart, Q., Nelson, R., Skog, K., Schmidt, A., Gray, E., and Jenkins, B., "Development of a biorefinery optimized biofuel supply curve for the Western United States," *Biomass and Bioenergy*, vol. 34, no. 11, pp. 1597–1607.

[87] Paulson, N. D. and Babcock, B. A., "The effects of uncertainty and contract structure in specialty grain markets," in *American Agricultural Economics Association Annual Meeting*, (Portland, OR), 2007. Selected paper presented at the American Agricultural Economics Association Annual Meeting, Portland Oregon, July.

[88] Perakis, G. and Roels, G., "The price of anarchy in supply chains: Quantifying the efficiency of price-only contracts," *Management Science*, vol. 53, no. 8, pp. 1249–1268, 2007.

[89] Perlack, R. D., Wright, L. L., Turhollow, A. F., Graham, R. L., Stokes, B. J., and Erbach, D. C., "Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply," tech. rep., Oak Ridge National Laboratory (ORNL), 2005.

[90] Pimentel, D. and Patzek, T. W., "Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower," *Natural Resources Research*, vol. 14, pp. 65–76, 2005. Number 1 March 2005.

[91] Preckel, P. V., Shively, G. E., Baker, T. G., Chu, M. C., and Burrell, J. E., "Contract incentives and excessive nitrogen use in agriculture," *Journal of Agricultural and Resource Economics*, vol. 25, no. 2, pp. 468–484, 2000.

[92] Rajagopal, D., Sexton, S. E., Roland-Holst, D., and Zilberman, D., "Challenge of biofuel: filling the tank without emptying the stomach?," *Environmental Research Letters*, vol. 2, no. 4, pp. 1–9, 2007.

[93] Rajagopal, D. and Zilberman, D., "Review of environmental, economic and policy aspects of biofuels," *SSRN eLibrary*, 2007.

[94] Ray, D. E., De La Torre Ugarte, D. G., Dicks, M., and Tiller, K., "The POLYSYS modeling framework: A documentation," tech. rep., Agricultural Policy Analysis Center (APAC), The University of Tennessee, Knoxville. http://www.agpolicy.org/polysys.html.

[95] Richard, T. L., "Challenges in scaling up biofuels infrastructure," *Science*, vol. 329, no. 5993, pp. 793–796, 2010.

[96] Rooney, W. L., Blumenthal, J., Bean, B., and Mullet, J. E., "Designing sorghum as a dedicated bioenergy feedstock," *Biofuels, Bioproducts and Biorefining*, vol. 1, no. 2, pp. 147–157, 2007.

[97] Salanie, B., *The economics of contracts: a primer*. The MIT Press, 1997.

[98] Schnepf, R., "High agricultural commodity prices: What are the issues?," tech. rep., CRS Report for Congress, 2008. RL34474.

[99] Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., and Yu, T. H., "Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change," *Science*, vol. 319, no. 5867, pp. 1238–1240, 2008.

[100] Service, R. F., "Is there a road ahead for cellulosic ethanol?," *Science*, vol. 329, no. 5993, pp. 784–785, 2010.

[101] Shapouri, H., Duffield, J. A., and Wang, M., "The energy balance of corn ethanol: an update," *USDA Agricultural Economic Report*, no. 814, 2002.

[102] Shumway, C. R., Pope, R. D., and Nash, E. K., "Allocatable fixed inputs and jointness in agricultural production: implications for economic modeling," *American Journal of Agricultural Economics*, vol. 66, no. 1, pp. 72–78, 1984.

[103] Spengler, J. J., "Vertical integration and antitrust policy," *The Journal of Political Economy*, vol. 58, no. 4, pp. 347–352, 1950.

[104] Sykuta, M. and Parcell, J., "Contract structure and design in identity–preserved soybean production.," *Review of Agricultural Economics*, vol. 25, no. 2, p. 332, 2003.

[105] Tilman, D., Socolow, R., Foley, J. A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., and Somerville, C., "Beneficial biofuels—the food, energy, and environment trilemma," *Science*, vol. 325, no. 5938, pp. 270–271, 2009.

[106] Tomlin, B., "Capacity investments in supply chains: Sharing the gain rather than sharing the pain," *Manufacturing & Service Operations Management*, vol. 5, no. 4, pp. 317–333, 2003.

[107] Tomlin, B. and Wang, Y., "On the value of mix flexibility and dual sourcing in unreliable newsvendor networks.," *Manufacturing & Service Operations Management*, vol. 7, no. 1, pp. 37 – 57, 2005.

[108] Tsay, A. A., Nahmias, S., and Agrawal, N., "Modeling supply chain contracts: A review," in *Quantitative models for supply chain management* (Tayur, S., Ganeshan, R., and Magazine, M., eds.), vol. 17, pp. 299–336, 1999.

[109] Tsay, A. A., "The quantity flexibility contract and supplier-customer incentives.," *Management Science*, vol. 45, no. 10, pp. 1339 – 1358, 1999.

[110] USDA, Economic Research Service, "Major land uses: Glossary." http://www.ers.usda.gov/data/majorlanduses/glossary.htm#cropland, Accessed: January 18, 2012.

[111] USDA, National Agricultural Statistics Service, "Tennessee cash rents, 2010." http://quickstats.nass.usda.gov.

[112] USDA, National Agricultural Statistics Service, "2010 State agriculture overview: Tennessee," tech. rep., 2011.

[113] USDA, National Agricultural Statistics Service, "Land values 2011 summary," tech. rep., 2011.

[114] USDA, National Agricultural Statistics Service, "Quick stats–U.S. & all states county data: Crops," 2011. http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats_1.0/index.asp, Accessed: June 8, 2011.

[115] USDA, National Agricultural Statistics Service, "USDA Crop values 2010 summary," tech. rep., 2011.

[116] USDA, United States Department of Agriculture, "USDA Agricultural projections to 2020," tech. rep., 2011.

[117] Van Mieghem, J. A., "Investment strategies for flexible resources," *Management Science*, vol. 44, no. 8, pp. pp. 1071–1078, 1998.

[118] von Braun, J., "Rising food prices: what should be done?," tech. rep., International Food Policy Research Institute (IFPRI), 2008.

[119] Wald, M. L., "A fine for not using a biofuel that doesn't exist, The New York Times," January 10 2012.

[120] Walsh, M. E., De La Torre Ugarte, D. G., Shapouri, H., and Slinsky, S. P., "Bioenergy crop production in the United States: potential quantities, land use changes, and economic impacts on the agricultural sector," *Environmental and Resource Economics*, vol. 24, no. 4, pp. 313–333, 2003.

[121] Walsh, M. E., English, B. C., and Jensen, K., "Agricultural impacts of biofuels production," *Journal of Agricultural and Applied Economics*, vol. 39, no. 2, pp. 365–372, 2007.

[122] Wang, M., Wu, M., and Huo, H., "Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types," *Environmental Research Letters*, vol. 2, no. 024001, pp. 1–13, 2007.

[123] Wang, Y. and Gerchak, Y., "Capacity games in assembly systems with uncertain demand.," *Manufacturing & Service Operations Management*, vol. 5, no. 3, pp. 252 – 267, 2003.

[124] Wilson, W. W. and Dahl, B., "Grain contracting strategies to induce delivery and performance in volatile markets," *Journal of Agricultural and Applied Economics*, vol. 41, no. 2, pp. 363–376, 2009.

[125] Wu, S. D., Erkoc, M., and Karabuk, S., "Managing capacity in the high-tech industry: A review of literature," *Engineering Economist*, vol. 50, no. 2, pp. 125–158, 2005.

[126] Yano, C. A. and Lee, H. L., "Lot sizing with random yields: A review," *Operations Research*, vol. 43, no. 2, pp. 311–334, 1995.

# VITA

Adaora Okwo was born in Manchester, England but grew up in Redondo Beach, California. She received her Bachelor's of Science and Engineering in Operations Research & Financial Engineering from Princeton University in 2005. Upon completion of her bachelor's degree, she moved to Atlanta, Georgia to pursue a doctorate at the Georgia Institute of Technology.